

14:49:28

OCA PAD AMENDMENT - PROJECT HEADER INFORMATION

12/14/94

Active

Project #: E-16-M50 Cost share #: E-16-352 Rev #: 1
Center # : 10/24-6-R7589-0A0 Center shr #: 10/22-1-F7589-0A0 OCA file #:
Contract#: DUE-9252303 Mod #: ADM. REVISION Work type : RES
Prime # : Document : GRANT
Contract entity: GTRC

Subprojects ? : N CFDA: 47.076
Main project # : PE #: N/A

Project unit: AERO ENGR Unit code: 02.010.110
Project director(s):
 KOMERATH N M AERO ENGR (404)894-3017

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 920815 to 950731 (performance) 951031 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	60,000.00
Funded	0.00	60,000.00
Cost sharing amount		6,667.00

Does subcontracting plan apply ? : N

Title: ILI-LLD: FLOW IMAGING AND CONTROL LABORATORY

PROJECT ADMINISTRATION DATA

OCA contact: Jacquelyn L. Bendall 894-4820

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Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : supplemental sheet
Equipment title vests with: Sponsor GIT

Administrative comments -

ISSUED TO EXTEND PROJECT TERMINATION DATE TO JULY 31, 1995 WITH FINAL REPORT
DUE OCTOBER 31, 1995.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION



NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 11/08/95

Project No. E-16-M50_____

Center No. 10/24-6-R7589-0A0_____

Project Director KOMERATH N M_____

School/Lab AERO ENGR_____

Sponsor NATL SCIENCE FOUNDATION/GENERAL_____

Contract/Grant No. DUE-9252303_____

Contract Entity GTRC

Prime Contract No. _____

Title ILI-LLD: FLOW IMAGING AND CONTROL LABORATORY_____

Effective Completion Date 950731 (Performance) 951031 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	N	_____
Final Report of Inventions and/or Subcontracts	N	_____
Government Property Inventory & Related Certificate	N	_____
Classified Material Certificate	N	_____
Release and Assignment	N	_____
Other _____	N	_____

Comments_____

LETTER OF CREDIT APPLIES. 98A SATISFIES PATENT REQUIREMENT. _____

Subproject Under Main Project No. _____

Continues Project No. _____

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Management	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other _____	N
_____	N

F 16-7150
1

Technical Progress Report for the Period 7/92 - 1/94

**NSF Contract No.
DUE-9252303**

FLOW IMAGING AND CONTROL LABORATORY

Work Performed at
GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF AEROSPACE ENGINEERING
ATLANTA, GEORGIA 30332-0150

Narayanan M. Komerath
Principal Investigator

**GITAER-EAG-94-4
February 1994**

FLOW IMAGING AND CONTROL LABORATORY NSF LLD Project Progress Report, February 1994

**Narayanan M. Komerath
School of Aerospace Engineering**

Summary

Using flow visualization and computer-assisted videography to generate an interactive image-based resource, an experiment is attempted to bridge the gap between the leading edge of technology and the undergraduate curriculum. The hypothesis is that the efficiency and productivity of learning fluid dynamics can be increased substantially by providing visual access to the dynamics of fluids, by enhancing hands-on participation, and by integrating the challenge of flow control into the curriculum. Progress in this experiment is described. The capabilities described in the proposal have been fully implemented within the first year of the project. Part of this was accomplished using additional institutional funds. As a result, funds remain for expanding and improving the equipment and instruments in the final period of the project. A summary of the equipment purchases to-date, an AIAA paper describing the progress on the technical part of the project, and a draft paper accepted for publication in the Proceedings of the DELOS'94 Conference, are attached in the Appendix.

INTRODUCTION

An experiment is underway to break out of the constraints which hinder us from efficiently linking the undergraduate curriculum to the leading edge of technology. This contract funds acquisition of the instrumentation to enable this experiment. The progress made towards acquiring this equipment is summarized. Changes in strategy and schedule from what was proposed are explained, and the benefits are discussed. To keep the report short, the major project description is left to the AIAA Paper attached in the Appendix. Since the ILI and LLD projects deal with the same subject, this report is a superset of the ILI report.

PROJECT STATUS / SURPRISES / CHANGES

1. In addition to the ILI equipment contract, we received an associated LLD grant to develop the curriculum experiment. The proposals for both LLD and ILI were for 1-year durations. The ILI was funded with a 2-year duration, though Institutional matching was for only 1 year. Period: 8/92 - 12/94. The LLD was funded for 3 years, 8/92 - 12/95.

2. Additional leverage allowed resources for student assistants. GTF/GTRC grants were received, in addition to the matching originally promised for this project:

1. \$33K in equipment for imaging / computing for research and instruction: '92

2. \$11K : Courses for student participation in research: 9/92 - 9/93

3. \$9K for safety course & study of ISO Lab Standards adoption: '94-'95.

3. Sharing of strategy, experience, and equipment with the SUCCEED program has resulted in some efficiencies, and a major expansion of the horizons of this project.

EFFECTS

The effect of these changes was to modify our plans as follows:

All proposed objectives except dissemination of course materials were met in Year 1.

An iterative approach was adopted to develop course materials and image-based problem solving technology.

Resources were leveraged and re-distributed to concentrate publication effort in the final year.

The opportunity to create a self-sustaining system was recognized, and utilized.

SUCCEED multimedia courses, software and equipment have become available to students participating in this project.

SUCCEED equipment for producing CD-ROMs has become available for the dissemination effort.

EQUIPMENT PURCHASES

The Institutional Matching money and additional institutional grant money was spent first, with all purchases completed by June 30, 1993. Savings due to delayed purchases were turned into superior equipment. As a result of the additional Institutional support, a sum of approximately \$40K remains for additional capabilities to be acquired during the remainder of 1994.

Additional capabilities being developed with help from research programs include a holography experiment, software and hardware systems for tomographic reconstruction from flow images, piezo-electric surface actuators, and experiments using an adaptive-controlled manipulator. In addition, LLD funds are being used to develop a water tank where imaging techniques have been developed by undergraduate assistants, and a short-duration vertical water tunnel, also being designed and installed by undergraduates.

COURSES

1. The Flow Diagnostics course (AE4010) was developed and taught as a senior elective in Winter 93, and the associated experiments were developed.
2. A new Flow Control course was taught as a senior elective (AE4813) in Spring 93. This was enabled by the experiments set up in AE4010, and by the students who had gained diagnostics experience in AE4010.
3. The Flow Diagnostics course is being repeated in Winter '94. The experiments are being refined, and the course materials improved.
4. Flow Control is being offered as an 8xxx course (open to both undergraduate and graduate students) in Spring '94. This has generated strong interest from other faculty. The lectures will be shared by three faculty members.

Curriculum Changes to-date:

1. In the junior level mandatory lab course, AE 3010, Vortex flow aerodynamics and an image analysis experiment were added in Fall '92, and repeated several times thereafter.
2. Problem sets are being developed: one each for AE3003, 3004, 3005, to be tried out in Spring 1994.
3. A Nonlinear Learning approach is being tried in AE4261, a Combustion elective course, where students are attempting problem-solving just ahead or parallel to the lectures. So far, this appears to be working very well, with student performance and interest levels exceeding expectations.

PUBLICATIONS

1. AIAA Conference Paper 92-4020 was presented at the Education Session of the Ground Testing Conference in Nashville, TN in July 1992, stating plans for the project.
2. AIAA Conference Paper 94-0850 was presented at one of the Education Sessions of the Aerospace Sciences Meeting in January 1994 stating technical aspects of project.
3. A Poster Session abstract has been accepted for presentation for the DELOS Conference in July '94
4. A paper describing the educational aspects of the experiment has been accepted for publication in the Proceedings of the DELOS Conference by peer review.

EVALUATION MECHANISMS

1. Anonymous, free-form and specific evaluation forms were given to each student in each course. The results were seen by instructor only after Institute tabulation, next quarter.

These were very positive and encouraging, and are summarized in the attached Draft paper for the DELOS conference.

(AE3010, Fall '92, AE4010, Winter '93, and AE4813, Spring '93 so far)

2. Presentations of work at the two AIAA Conferences were used to gauge audience reactions. These were quite positive.

3. Acceptance of a paper by peer review for the DELOS Conference indicates some acceptance of the work in the educational community.

APPENDIX I

PROPOSED AND ACTUAL EQUIPMENT PURCHASES

The following Table compares the proposed equipment list (from Dec. 1991) and the actual purchases to-date (February 1993). The savings due to additional Georgia Tech grants, and due to the use of equipment from research labs are shown. The savings are expected to be translated into equipment needed to improve or add experiments during this year, based on iterative experience.

Item	budgeted	spent	Comments
Argon laser : 5-watt	32189	36943.96	6-watt, adds automatic beam control
spare tube	11500		not bought yet
Laser Base	3325	1255	new vendor found
Coherent safety glasses	1600	1276.96	
FiberOptic System for LDV& laser sheet	34483	40725.94	inflation and more complete system
Miscellaneous Optics	5000	5182.48	adds holography kit
Acousto-Optic Modulator	2470	3097.11	inflation
vibrating mirror	2000	0	not bought yet
PULNIX NV700 Intensified camera system (2)	16788	0	GTRC eqpt. grant
Sony 19" monitors 2	1000	0	GTRC eqpt. grant
HAMA Videocut 11 Editing Controller	1700	0	GTRC eqpt. grant
Sony V-101Video camera	1169	2225	CanonA-1: better camera
Video Recorder (2)	3000	0	GTRC
Video Recorder/Player	650	0	not bought yet
RasterOps frame grabber system #1	2700	2371	VideoSpigot: Quicktime frame grabber system
RasterOps frame grabber system #2	2700	2599	R-O XLTV: Research
RasterOps frame grabber system #3	2700	0	R-O XLTV: Research
Macintosh Quadra computer system 900 #1	7500	6970	Q700 w/24MB RAM
Quadra 900 computer #2	7500	6976.95	Quadra 800CDw/40MB RAM, 500MBdisk & software
Quadra 900 #3	7500	6323	Q800 system
Ocean Sys 256MB optical storage system#1	4443	3358	
Optical Drives(256MB w/diskettes)(system#2)	4443	0	from research projects
Optical Drives(256MB w/diskettes)(system#3)	4443		not bought yet
Apple Laserwriter NTX 300dpi printer	3950	1619	HP Laserjet4M: 600dpi printer
Misc. items	2400	1756.62	
Gateway2000 486 66MHz computer	0	4720	added this computer for faster SCV processing
TOTAL	167153	127400.02	

APPENDIX II

✓
ILI94P05

To:

Dr. Narayanan M. Komerath
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332
narayanan.m.komerath@aerospace.gatech.edu

From: Dr. C. Stewart Slater

Manhattan College

ASEE-DELOS/NSF Poster Session Review Committee

Re: Paper for the 1994 ASEE Annual Meeting - NSF/DELOS Poster
Session. Review for Conference Proceedings.

1. This memorandum contains results of the review of your
submitted paper for inclusion in the 1994 ASEE Conference
Proceedings. Comments from peer reviewers have been summarized
below.

2. The result of the review of your paper is:

☒ Accepted as submitted.

☐ Accepted subject to revision as noted.

☐ Rejected. Rationale noted below.

Reviewer's comments:

Well written with thorough detail.

3. ASEE will send the instructions for preparation of the paper
for the Proceedings directly to you. If you do not receive these
by the first week of March contact ASEE directly. PLEASE follow
their directions to correctly format your paper.

4. The committee collectively wishes to thank you for
participating in this ASEE-NSF joint venture of disseminating the
results of your ILI project.

FLOW IMAGING AND CONTROL LAB:
AN EXPERIMENT IN ITERATIVE LEARNING

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Georgia Institute of Technology
Atlanta, Georgia 30332

Abstract

Techniques for controlling fluid dynamics provide a multidisciplinary challenge to engineering students. Modern flow diagnostic techniques have been implemented in a new laboratory to bring undergraduate fluid dynamics curricula to the forefront of technology. This requires a large increase in the efficiency of learning. An iterative learning approach, based on flow visualization and digital image processing, is proposed to achieve this efficiency. Several of the traditional constraints hindering laboratory development have been eliminated by enlisting the assistance of the students, mostly undergraduates taking full-time course loads. Surprising student reactions to the courses taught using the new laboratory reinforce the evidence that there are viable alternatives to the traditionally linear approach to learning engineering fluid dynamics.

INTRODUCTION

This paper describes the educational aspects of an experiment to link the undergraduate curriculum to the leading edge of technology. The technical area of interest is in unsteady fluid dynamics and flow control. Ref. 1 introduced the project described in this paper, at its inception, and laid out the objectives. Ref. 2 reported on the technical details of the resulting laboratory and new courses, a year later. Here the educational aspects are considered, using student evaluations and the instructor's observations to draw conclusions.

Problem Statement

Many of the following concerns may apply to other disciplines as well, but the area of the author's interest is fluid mechanics. Advances in numerical simulations, diagnostic techniques, micro-mechanics, integrated circuits, and control techniques have opened the way to many applications which were impractical when today's

teachers were undergraduates. High-lift devices, artificial hearts, cryogenic turbines, fluidic cutting tools, fluid bearings, and techniques for drag reduction, jet deflection, noise cancellation, mixing enhancement, and vibration control are becoming common parts of engineering practice. These are far removed from the steady laminar flow calculation methods taught in the undergraduate curriculum.

Present and future graduates must thrive in an environment which cannot afford long training periods or close technical mentoring. Success depends on quick and accurate response to customer needs. Thus there is a clear need to close the gap between the undergraduate curriculum and the leading edge of technology, without compromising scientific discipline. At the same time, the pressures from advances in every field, the demands to broaden engineering education, and the pressure to shorten the time to graduation, all mean that no additional time will be available to teach the advanced material required to bring our undergraduates up to an ever-receding target: the leading edge of technology. The issue in this paper is how to achieve a self-sustaining curriculum which will get the graduates of the future to this receding target without missing the important basic education of yesterday's graduates.

Hypothesis

The principal hypothesis of this project is that there are viable "non-linear" approaches to learning fluid dynamics. As described in Ref. 2, we attempt an approach where the student starts working with sophisticated tools which *enable early exposure to the realities* of fluid dynamics and its applications. The students' enhanced "feel" for the subject must then enable a total reorganization of the learning sequence to achieve a more efficient path from the basic concepts to the leading edge of technology. There are two key elements to the approach: 1) The integration of modern diagnostic techniques and analysis tools into the curriculum from the beginning, and 2) the experience of *attempting to achieve* specified results using real flows. The graduate of such a

¹: Associate Professor. Associate Fellow, AIAA.
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curriculum should gain basic and detailed knowledge of the subject, as well as experience in using modern tools, *with no sacrifice, and indeed a large advantage*, in theoretical rigor.

Supporting Arguments

In support of this hypothesis, we consider the following:

1. Typical lecture methods allow little student participation, because facts and arguments are pipelined to be delivered in a carefully ordered sequence to the student, with little feedback. Thus, for example, students often must grasp the mathematics of the Helmholtz vortex theorems before observing a wing with its tip vortices. A live course can be a joint exploration as opposed to a one-way information transmittal.
2. The efficiency of comprehension for most students is far below 100%. To paraphrase a famous saying, much of what is taught "passes from the notes of the instructor to the notes of the student without passing through the brains of either".
3. Since intermediate diplomas are not given, what matters is the student's integrated state of knowledge and competence *at the end of the program*. Thus it is acceptable that some of the "fundamentals" do not become clear until late in the senior year, as long as there is an opportunity *to re-examine the lessons* of the previous courses in the light of the new knowledge. This is possible using modern technology, and, given Item 2 above, is not necessarily less efficient than the present learning sequence.
4. Iteration and frequent failure are keys to excellence in learning and comprehension: this is why on-the-job learning is so effective in building confidence. School is the ideal place to learn how to experiment, anticipate failure, and survive it, if this can be done without the lifelong penalty of poor grades. At the same time, most of us need a considerable amount of external "pressure" to learn to perform far beyond our previous ideas of our own true limits. An integrated curriculum which combines iteration with discipline can outperform current "quantized" curricula, because the overall efficiency of the learning process can be much higher.
4. In Ref. 1, it is argued that experiments are essential to gain "physical insight", a quality that is always cited as lacking in new graduates. For the immediate future, such experiments will have to be performed using information extracted from actual flows. However, modern technology makes it unnecessary to do all of the experimenting in real-time, a prohibitively expensive proposition: much can be done with

recorded images and numerical tools. The required tools have become cheap and accessible: thus some things can indeed be done in education that were impractical a few years ago.

Previous Work

The NSF Workshop on Fluid Mechanics³ in Fall '86 emphasized the usability of Fluids technology and identified shortcomings in current curricula. The opportunity to design more integrated learning methods is being recognized. Beasley, Culkowski, and Gufner⁴ describe integration of laboratory, lecture, and office space, where students use full-scale equipment to quickly test out what they learn in the classroom. This recognizes the advantages of "learning on the job", a concept similar to what is advocated here. Lamancusa⁵ reports on a laboratory aimed at giving mechanical engineering students an integrated look at electronics and computer interfacing.

Alam, Bakos, and O'Leary⁶ explore the opportunities offered by new video and computer technology in designing an "Image Database", an "instructional picture database" for a pavement design class. They used PC-type computers, with an optical disk drive and image capture and video systems. They explored the requirements of storage, transmittal, retrieval, and usage. Van Valkenburg⁷ advocates "tutored video instruction" as the preferred mode of teaching of the future, as a superior alternative to large-group lectures. Again, the opportunities presented by the high-speed workstation as a semi-intelligent information source are recognized. Greenfield⁸ discusses the impact of new CD-ROM technology on Integrated Learning Systems.

Harb et al⁹ emphasize "teaching through the cycle", referring to the four quadrants of the Kolb learning cycle. In this cycle, the learning process must go through each of the following aspects: reflective observation, concrete experience, active experimentation, and abstract conceptualization.

Evans et al¹⁰ present findings of a project aimed at exploring curriculum changes to better prepare engineers for the practice of their profession. They identify a set of desirable attributes, and prioritize them according to the preferences of students, industry, faculty, and alumni. Among the generic recommendations are the needs for improved laboratory experience, open-ended projects, contextual settings for course subject matter, and teaming skills. Bengelink et al¹¹ provide an industry perspective on the same subject. Quinn¹² cautions against

the decline of the study and practice of experimentation in the undergraduate curriculum and presents results of a new program established at Drexel University where experimentation is integrated into the curriculum from the beginning.

Relation to Present Work

The curriculum discussed here uses technological capabilities similar to what is advocated by these educators. The setting of the present project is a School which is very heavily involved in sponsored research, yet maintains an extremely strong commitment to excellence in its undergraduate program. The constraints of such an environment are examined before laying out the solution approach. The experience of the first cycle of the experiment is analyzed.

Constraints

The constraints facing a developer of a curriculum experiment centered around a laboratory in the present setting are listed below, summarized from Ref. 2:

1. The extensive time and effort involved in obtaining resources, and then in getting the new equipment through the university/State purchasing system.
2. Lack of space in the curriculum for labs, since the popularity, easy access, and perceived utility of numerical approaches leaves little room for laboratory courses.
3. Laboratory hours count less in the university credit system. Students find lab workloads to be disproportionate to the credit assigned. The instructor finds that a lab takes thrice as much time and earns 2/3 the pay of a theory course.
4. Preparation for a lab requires detailed instruction manuals, extensive testing and competent teaching assistants.
6. Faculty involved in research must seek external funding to develop courses, because institutional course development funds are scarce. Research is crucial to the link between the curriculum and the leading edge of technology.
7. Worries about safety can destroy the remaining resolve of the aspiring lab developer.
8. Even such generous grants as those which fund this program have limited lifespans. If the lab is to flourish after the period of the development grant, a mechanism for self-sustainment is vital.
9. Time spent on lab development reduces "productivity" in number of refereed papers, and counts far less in the faculty evaluation system.
10. By comparison, lecturing on theory from last year's notes is painless, ensures excellent student

evaluations of the instructor's "knowledge of the subject", and keeps the administration happy.

These constraints stem from complex pressures, some of which the present author understands. However, any lasting solution must recognize and address these constraints.

The NSF-ILI and LLD programs

In August 1992, the NSF funded a project at the School of Aerospace Engineering at Georgia Tech under the Leadership in Laboratory Development initiative, along with an equipment grant. The core of this curriculum experiment is illustrated in Figure 1 and includes a self-sustaining technology transfer mechanism. The project attempts to: a) bring the *dynamics* of flows into the curriculum and the problem-solving process using digital image processing, b) enable flow-control experiments, and c) enable students to try independent experimental projects. These efforts aim to give the engineering graduate the comprehension, experience, and confidence to use advanced concepts and techniques in fluids engineering. Flow control is chosen as a vehicle for the curriculum experiment because it is a topic of intense research and vast opportunities, and because it challenges the student to try to achieve specified results in flows, discovering many unexpected things in the process. Flow diagnostics is an essential part of the experiment because it introduces the sophisticated tools and methods needed to detect, observe and measure the phenomena which are to be controlled. Both of these topics are also extremely rich in their use of diverse fields of physical sciences.

Conventional vs. Iterative Curricula

The linkage between the different portions of the experimental curriculum is illustrated in Fig. 1. The basic exposure to experimental techniques and laboratory practices gained in AE3010 enables the student to start using the advanced tools of AE4010, the Diagnostics course. In turn, this experience is immediately put to use in the Flow Control course, with each student team containing at least one student veteran of AE4010. The courses have the obvious intent of recruiting some students into research programs using independent Special Problems. All of these courses, and the research program, provide additional material to be incorporated into the image database and thence into problem-solving.

The iterative curriculum is contrasted with the traditional approach in Fig. 2. In the

traditional curriculum, we organize the sequence in which things must be learned, and feed the topics one a time, testing "mastery" at every stage. This is akin to the von Neumann approach to digital computer algorithms: no information must be provided that cannot be totally understood using previously-defined information. This forces us to use extremely simplified problems for illustration and examinations. The student is sheltered, but our evidence indicates that this sheltering is not appreciated by active minds. In addition, this approach assumes that the information presented is absorbed with an efficiency of 100%. This may be far removed from reality, since most human minds quickly discard information which is not supported by experience.

In the iterative approach, we spend a minimal amount of time on introductory lectures, and then set the student to work on real flow problems from the image database. The initial questions will of course be simple, but the whole complexity of the flow is right there, challenging the student to try to understand the flow better. The answers to problems will not be as clean as would occur if the problem were idealized. This would serve to remove the fear of imperfection, and encourage the search for the reasons for the inaccuracy. In this context, theoretical methods and diagnostic techniques become helpful tools, rather than topics for "rote memorization". The next step is to pose flow control problems, which demand much more insight, analytical ability, and innovative spirit than flow analysis problems. The database now becomes a source of answers. It also serves to test out diagnostic techniques and analytical tools. Once adequately developed, the image database should serve all the courses in the curriculum. Thus we anticipate that no major revolution is needed in the course sequencing: the iterative approach can be worked right into the present curriculum.

Link to the present curriculum

Figure 3 presents the structure of the present curriculum. Fig. 4 lists the experiments of the present AE3010, the only lab course in the mandatory "core" curriculum in fluid dynamics (there are corresponding labs in Structures and Controls). This is, no doubt, a state-of-the-art curriculum, fine-tuned through several major and minor changes, and carefully meshed with pre-requisite and follow-on courses in the other disciplines. One major need for a curriculum experiment in this environment is that it has become extremely difficult to make

improvements or revisions to this curriculum, given the tight integration of the course sequencing. It appears to be essential to break out of the "pre-requisite" system if the curriculum is to change rapidly enough to keep up with changing technology.

Experiment No. 1: Open-ended analysis in the junior lab

In the Fall of 1992, an experiment was added to AE 3010, the junior lab. A short lecture in vortex flows at high angles of incidence was followed by an assignment where students had to track vortex trajectories over an aircraft model. The information came from a videotape generated the previous summer on a research project by an undergraduate (Ref. 13). The assignment was vague to many students because it is much harder to locate the "center" of a fuzzy pattern than it is to draw a circle around a given point. However, their confidence level was boosted when they realized that the instructor had no idea of where the center was, either. The trajectories, plotted independently for the two sides of the aircraft, matched surprisingly well, proving the accuracy of the students' judgement. The other result was that the video digitization and timing procedures, which we had learned in the research lab just the previous summer, became commonplace to the juniors as a problem-solving tool. The vortex flow phenomenon was not covered elsewhere in the curriculum: it was just observed as a reality.

Experiment No. 2: Concurrent Learning and Course Development

Figure 5 shows the organization of AE4010, the Flow Diagnostics course, taught in Winter '93. Here we experimented with a way to break out of the "lab development" and "teaching assistant" constraints. The lectures covered modern diagnostic techniques in detail, but were divided into three concurrent areas, so that student teams could make progress on three different experiments at the same time. Each team got one complex experiment ready in the first six weeks of the quarter, along with a computerized instruction manual. In the remaining time, each team "hosted" the other students and guided them through their experiment. The experiments and instruction manuals were refined by experience. The successful experiments were videotaped for the image database. The competition and pressure to perform were limited to the quality of the work on developing experiments, the quality of the manuals developed, and the quality of the presentations at the end of the quarter on each experiment. Each team also reported on their

experience and suggestions for the other experiments.

Experiment No. 3: Link to current research

In Spring 1993, the Flow Control course was offered. The course organization is shown in Fig. 6. Here the instructor was obviously learning along with the students, with his sole advantages being in the ability to guide the proceedings and interpret ideas based on experience. A literature search was performed, and review papers were extensively used in lectures^{14,15}. Following this, students were asked to choose one or two papers to study, summarize, and present to the class for discussion. The involvement and comprehension levels of the class in these presentations far surpassed those of usual lectures. To help get their experiments working, the students toured research facilities and obtained specialized advice from experts.

Experiment No. 3: Research participation by undergraduates

Over the years, many undergraduates have provided evidence of the feasibility of such a project. Ref. 16 described the installation and testing of a laser Doppler velocimeter for a complex rotor flow measurement. Ref. 17 developed some of the laser sheet imaging techniques used here. Ref. 18 documents the conversion of a time-series analysis system from the research wind tunnel to the 42" tunnel used in the undergraduate lab. Ref. 19 tested image analysis methods in the wake of a cylinder. Ref. 20 obtained dynamic schlieren videographs of the starting and shutdown of a supersonic wind tunnel. Ref. 21 tested the Spatial Correlation Velocimetry technique in a simple experiment without using lasers. The NSF project provided an umbrella to involve undergraduates at all levels. The Georgia Tech Foundation provided resources to employ students in research projects. To-date, 12 undergraduates have participated in various parts of the year as assistants in both the course development and associated research efforts. Of these, 4 started when they were freshmen, 5 as sophomores, and 3 as juniors. These are full-time students, taking 15 to 17 credit-hours per quarter. As such, their working hours are scattered throughout the week.

Student reactions

In AE3010, the most surprising aspect was that the new experiment brought very little comment: the fact that they had done something which was not covered in lectures or their textbooks did not bother anyone. The overall

satisfaction level with the course exceeded all previous evaluations, *despite the increase in the workload*, which was the most prevalent complaint of previous quarters. In AE4010, the "Small-Class Evaluation" form was used. Students were asked to respond to 3 questions: 1) How well did the instructor prepare and present the course? 2) How effectively did the instructor interact with the students? 3) How effective was the instructor in evaluating and grading student performance? Comments related to the course are quoted below:

"the lab work provided the best learning experience"

"the best part was worrying about trying to get the experiment working and getting good data as opposed to getting a report done on time"

"this was the first time this class was taught. As a result, the labs were new and full of 'problems'. The course was prepared in a well organized manner although much of the organization was done by the students during the quarter. I like this form of class because it is 'hands-on' and experience is the best teacher".

"We really got a chance to develop our own ways to try the experiments. I felt I not only learned the material but gained a lot of knowledge in terms of real research"

"the grading was exactly as it should have been".
.."evaluated on our work and presentation instead of the ability to spit back a bunch of memorized facts"

"while the theory behind the experiments was covered in detail, the results expected were only to be found by running the experiment. I quickly found that nothing ever goes as planned. Despite this, it was pretty cool to know that when you got the answer, you earned it"

"although at times frustrating the class was definitely worth it"

"especially liked the fact that the class was graded on conceptual understanding rather than rote memorization"

In AE4813, our conventional numerical rating system was used, with space for free-form comments. The specific comments were:

"good overview of what is going on in the field of flow control. Reading and discussing papers was a good way to learn. I would have enjoyed it even more if the experiments worked..but that's the life of an experimentalist, right?"

"flow control was a bit abstract, but a great way to delve into something that isn't black & white. Using the lab as a testing ground, failures as well as success provided a real learning process. The ability to choose something of your own interest made it even better. The instructor was willing to

help and advise in order to hopefully keep things moving forward.
"keep the course - it's great to actually use what you learn.

The author notes that the roster in both classes was unusually high in academic achievement. Such acceptance of frustration and challenge, and tolerance of a less-than-perfectly organized course are unlikely to be found in general in the average "required" course. Also, it was a sobering surprise to hear our normal testing methods described as "rote memorization". The important finding, though, is the very high level of satisfaction with a challenging and supposedly frustrating experience. This makes one wonder about the need for extensive preparation to spare the student from surprises and imperfections in the lab, provided that a safe environment is always maintained.

Supportive evidence for the hypothesis comes from all three courses taught under this scheme to-date. The students who analyzed vortex trajectories in AE3010 had never had a theoretical lecture on vortex-dominated flows, nor indeed any occasion to consider even swept wings. The presenters of summaries of research papers in AE4813 ventured far from what they were supposed to have learned. The instructor in any conventional curriculum would have been unable to introduce even the concept of these papers in a one-way information transmittal. In the relaxed setting of the student presentations, after the students had gone through one iteration of struggling with the papers, these concepts were easily conveyed through discussion, and set in terms that the students understood. This is an example of the "non-linearity" of the iterative learning process.

CONCLUSIONS

1. An experiment is underway to break out of the constraints that hinder a permanent linkage between the undergraduate curriculum and the leading edge of technology.
2. One cycle of this iterative experiment has been performed successfully.
3. State-of-the-art video digitization and flow imaging techniques have been successfully added to a junior-level mandatory course.
4. Two laboratory courses have been developed, primarily by the students themselves.
5. Instruction manuals for these laboratories have been developed by the students and refined through customer experience.

6. In teaching these courses, a large amount of new material has been added to an image database to provide a mechanism for self-sustainment of the laboratory.

7. A new course on Flow Control provides a mechanism to keep the curriculum linked to current research.

8. Full-time undergraduates at the freshman through senior levels have proved to be excellent resources in interfacing the research programs and undergraduate curricula.

ACKNOWLEDGEMENTS

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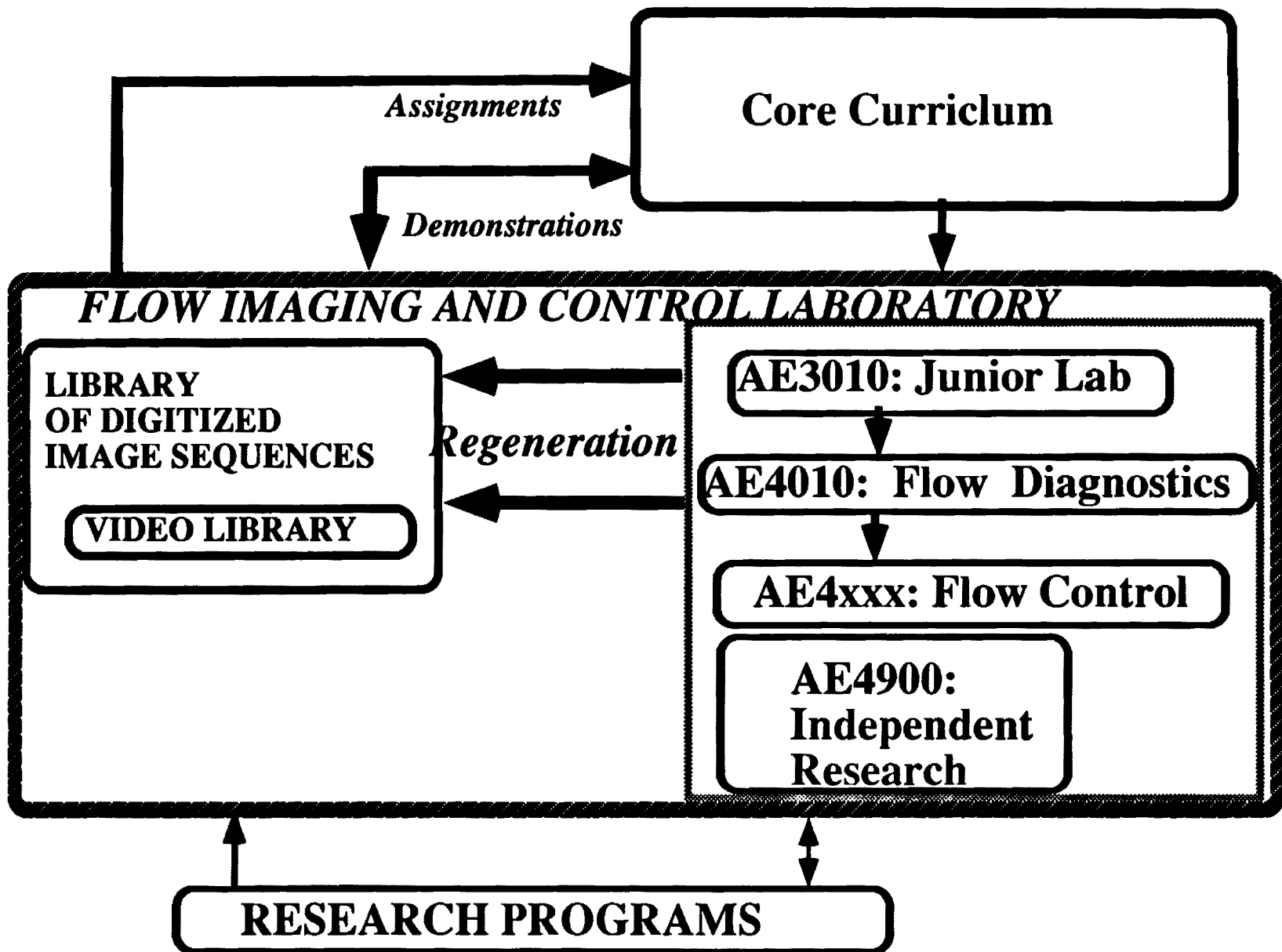


Figure 1: Flow Imaging and Control Laboratory Concept

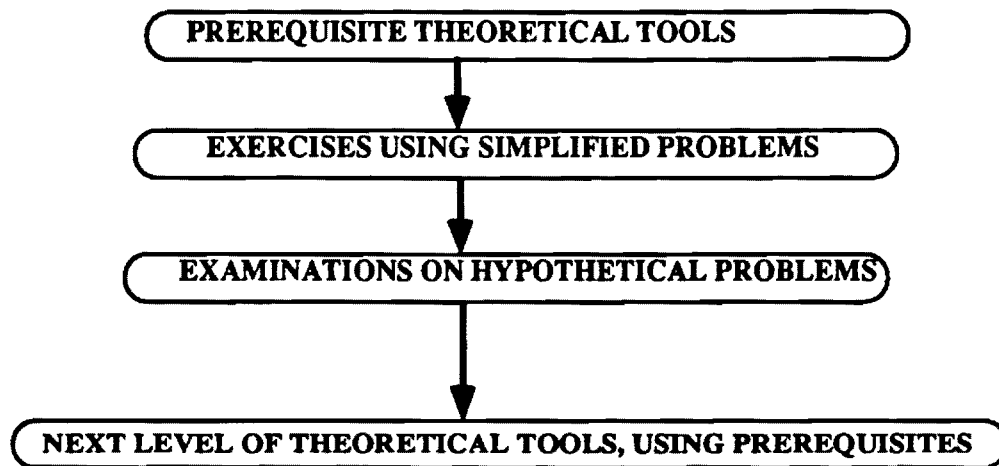


Figure 2(a): Conventional Engineering Curricula are arranged sequentially

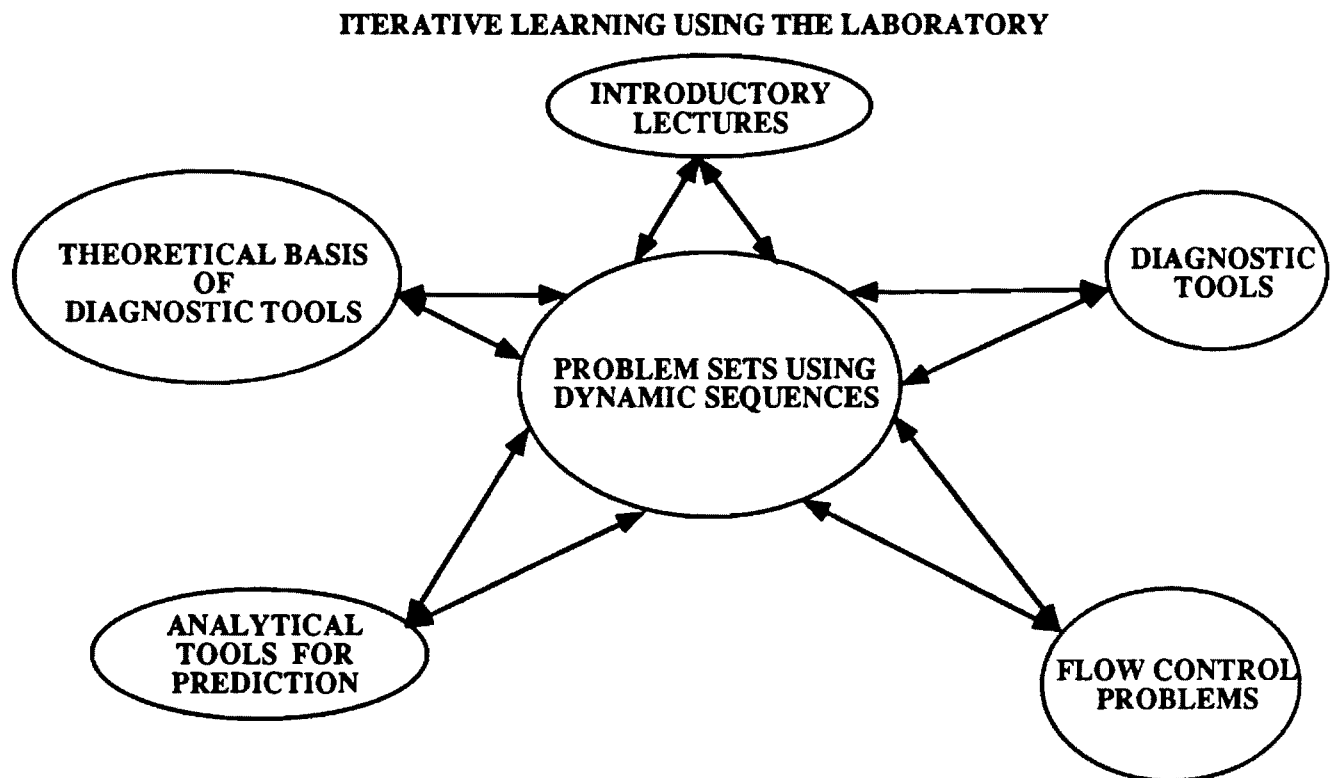


Figure 2(b): Iterative Curriculum Using an Image Database

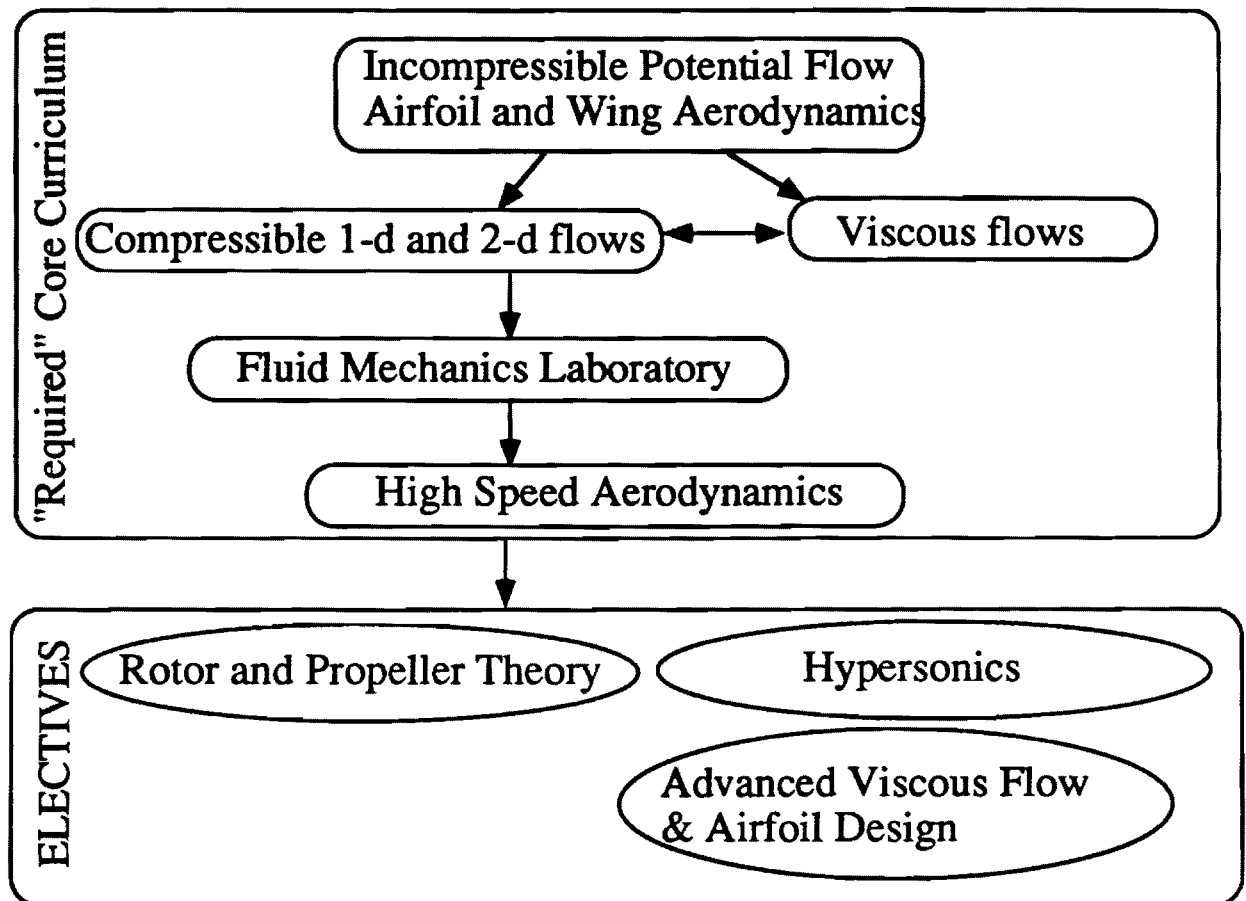
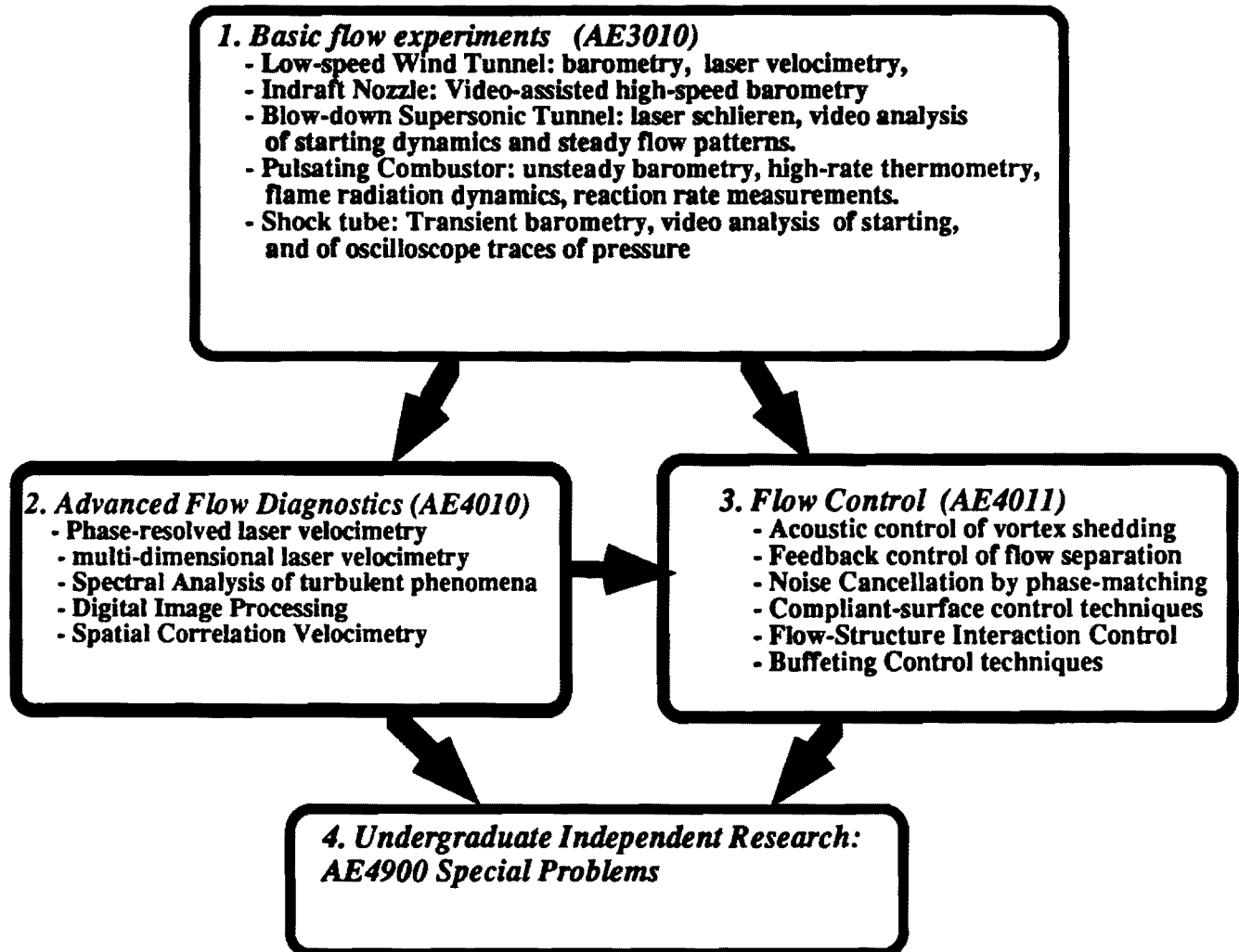


Figure 3: Present Fluid Mechanics/Aerodynamics Curriculum

FLOW IMAGING AND CONTROL LAB: A MODEL FOR THE FUTURE



Figs 4,5,6 [under construction]

Figure 2, showing information flow between the different experiences of the laboratory sequence.



AIAA 94-0850
Experimental Curriculum in Diagnostics
and Control of Unsteady Flows

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32nd Aerospace Sciences
Meeting & Exhibit
January 10-13, 1994 / Reno, NV

Experimental Curriculum in Diagnostics and Control of Unsteady Flows

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ABSTRACT

Experimental aerodynamics is an excellent vehicle for integrating an engineering curriculum. Using flow visualization and computer-assisted videography to generate an interactive image-based resource, an experiment is attempted to bridge the gap between the leading edge of technology and the undergraduate curriculum. The hypothesis is that the efficiency and productivity of learning fluid dynamics can be increased substantially by providing visual access to the dynamics of fluids, by enhancing hands-on participation, and by integrating the challenge of flow control into the curriculum. Progress in this experiment is described. Modern diagnostic capabilities have been added. Two new courses in diagnostics and control of fluid dynamics have been tested, the results of research are being integrated into the required portion of the curriculum, and an interactive visual database has been established. Several of the traditional constraints hindering laboratory development have been eliminated by enlisting the assistance of students at all levels.

INTRODUCTION

An experiment is underway to break out of the constraints which hinder us from efficiently linking the undergraduate curriculum to the leading edge of technology. In this paper, the hypothesis of the experiment, the constraints and the strategy for implementation are described. The technical aspects of the experiment are discussed, and the progress summarized.

A vehicle for learning engineering

Experimental aerodynamics takes the researcher into several areas of engineering, some far removed from fluid mechanics. Fig. 1 attempts to summarize these. The skills normally associated with the aerodynamicist are in the calculation or measurement of flow-induced forces on airfoils and aircraft-like configurations. However, many of the problems

involve acoustics, vibrations, and aero-elastic phenomena. Mechanical design and cost-effective fabrication are essential. To measure loads, for example, the experimenter must choose from a multitude of physical phenomena and sensor technologies subject to various constraints. Flow visualization requires the effective use of optics and video technology. Data analysis requires probability and statistics, leading into signal processing and integral transform techniques. Diagnostic techniques lead into lasers and laser-induced phenomena. Image processing enables extraction of quantitative results from video. Robotics and control technologies offer attractive solutions to move models and probes. They also open up a new world of flow control techniques. The experimenter must use numerical techniques to predict the "expected" flow features, requiring entry into high-speed computing. In addition, the student experimenter must learn to work with expert machinists, who quickly teach simplicity and realism in design, and to improvise the right level of technology (even if it is modeling wax and tape) for the job.

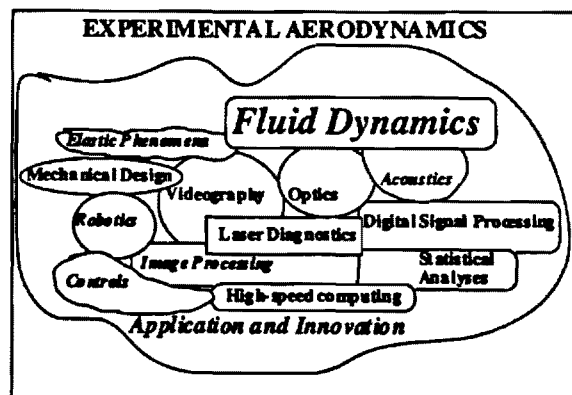


Figure 1: Discipline interactions in experimental aerodynamics.

Experimental aerodynamics thus offers opportunities for innovation, and reasons to be curious about all fields of engineering and physical sciences, and to overcome the fear of learning new things without formal courses. On the other hand, this may be an excellent way to address many of the criticisms widely leveled at today's graduates and their instructors^{1,2}.

¹: Associate Professor. Associate Fellow, AIAA.
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Need for Change in Fluids Curricula

Advances in various fields have enabled several things which were regarded as science fiction when today's teachers were undergraduates. In the past, to counter industrial criticism about new employees requiring extensive training, we have argued that the aim of the undergraduate curriculum is to teach the "fundamentals", and the "techniques of life-long-learning". Until recently, the primary employers of aerospace graduates were the major aerospace manufacturers and the government. It was assumed that these organizations would not, in any case, assign critical responsibilities to the new graduate without a long period of specialized training. The criticism about the graduate's lack of ready-made practical sense and preference for theoretical as opposed to applied work is universal. For example, Ref. 3 cites essentially the same concerns about graduates of the elite Moscow Institute of Mechanics, and their eventual maturing into capable experts. We have been successful in "life-long learning", and the aerospace engineer has always demonstrated versatility and problem-solving ability.

The times have changed. The new market for aerospace engineers is as much in small companies as in large ones, and versatility is more important than ever. The small group environment lacks the resources to provide technical mentoring or long training periods. Thus there is a clear need to close the gap between the undergraduate curriculum and the leading edge of technology, without compromising scientific discipline. Of the 200-plus quarter-credits needed for graduation, the aerospace "core" curriculum is typically limited to less than 40 credit-hours (13 courses), with much of the rest devoted to "things every engineer must know", or "topics to broaden the engineer's mind", as defined by State and Accreditation Board rules. Given the long list of prerequisites for advanced courses, it is easy to see why the technology gap is widening.

THE PRESENT CURRICULUM

The undergraduate fluids curriculum at Georgia Tech's School of Aerospace Engineering begins with AE3003 introducing potential flow theory, and the analysis of steady incompressible aerodynamics of airfoils and finite wings. AE3004 enables quasi-1-d analysis of nozzle flows, moving shocks, supersonic tunnel starting problems, flows with friction and heat addition, and goes on to oblique shocks, Prandtl-Meyer expansions, and nozzle exit flows. AE3005

teaches analyses of steady shear layers. AE4001 covers linearized high-speed aerodynamics. Beyond the core, students choose from a range of advanced elective courses on computational fluid dynamics, hypersonics, viscous flow, and rotor aerodynamics. The only laboratory course in the core is the 2-credit AE3010, which serves many purposes. Groups of 3 to 5 students operate a series of eight experiments. The grading of lab reports emphasizes technical reporting standards. Towards the end of the quarter, each student is assigned a hypothetical measurement problem which usually requires a literature survey, thinking, and originality. The final exam is a 10-minute presentation of the proposed solution, with questions from the audience and instructors.

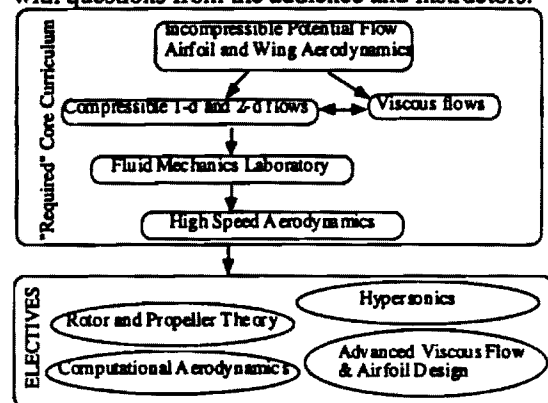


Figure 2: The present undergraduate curriculum in fluid mechanics.

The present curriculum meshes closely with pre-requisite and interdependent courses in other disciplines. There have been continuing advances in the professional skills of the graduating engineer. As one of its developers, the author takes great pride in the curriculum and its graduates. However, the challenge of developing experimental skills and physical insight remains, with little time available for these. The various pressures on the curriculum have left little maneuvering room, so that future advances require new approaches.

The NSF-ILI and LLD programs

In August 1992, the NSF funded a project under the Leadership in Laboratory Development initiative, along with an equipment grant. The project attempts to: a) bring the *dynamics* of flows into the curriculum and the problem-solving process using digital image processing, b) enable flow-control experiments, and c) enable students to try independent experimental projects. These aim to impart the comprehension, experience and confidence to use advanced concepts and techniques in fluids engineering.

HYPOTHESIS

The principal hypothesis is that there are viable "non-linear" approaches to learning fluid dynamics. We attempt an approach where the student starts working with sophisticated tools which enable early exposure to the realities of fluid dynamics and its applications. Once the system is in place, we expect to reorganize the learning sequence, cutting the time now spent on some topics which were "basic" when our teachers' teachers were undergraduates. In the time taken to teach the present curriculum, the student who has better experience of "seeing" and working with flow phenomena can gain more basic and detailed knowledge of the subject, as well as experience in using modern tools, *with no sacrifice, and indeed a large advantage*, in theoretical rigor. Doubtless, considerable risk is involved in this apparent "something-for-nothing" hypothesis. We have no intention of setting up "control" groups of students to test the hypothesis at the risk of the students; instead the experiment is being worked into the existing curriculum. Many things must come together before the approach can work. In this paper, the progress made along these lines is described.

Constraints facing a developer of an experimental curriculum

Before setting out on an ambitious project, it is vital to understand the true constraints:

1. Most of the time available to set up a laboratory is lost in the paperwork and drudgery of the purchasing and plumbing phases.
2. Numerical approaches have displaced experimental ones in the curriculum because they are easier to access and perceived to be more generally applicable.
3. Laboratory hours count less in the university credit system. Usually, a 3 hour-per-week lecture course earns 3 credits while a lab course earns 2 credits. Students find lab workloads to be disproportionate to the credit assigned. For the instructor, the lab takes thrice as much real time and earns 2/3 as much pay as a theory course.
4. Preparation for a lab requires detailed instruction manuals, extensive testing and competent teaching assistants. Graduate students with such skills are too valuable in the research programs to be spared for TA assignments.
6. Technology transfer to the undergraduate curriculum requires the instructor to be constantly learning new things, usually from current research experience. Researchers find it harder to get Institutional course development funds because they are considered to be too busy.
7. Worries about safety can destroy the remaining resolve of the aspiring lab developer.

8. Even such generous grants as those which fund this program have limited lifespans. If the lab is to flourish without external support, a mechanism for self-sustainment is vital.

9. Time spent on lab development reduces "productivity" in number of refereed papers, and counts far less in the faculty evaluation system.

10. Everyone learns eventually that lecturing on theory from last year's notes is painless, ensures excellent student evaluations of the instructor's knowledge of the subject, lowers stress, and keeps the administration happy.

These constraints stem from complex pressures, some of which the present author understands. The problems are fairly universal, but the constraints must be recognized to avoid unrealistic expectations.

PROGRESS TOWARDS THE NEW CURRICULUM

The core of this curriculum experiment is illustrated in Fig. 3 and includes a self-sustaining technology transfer mechanism.

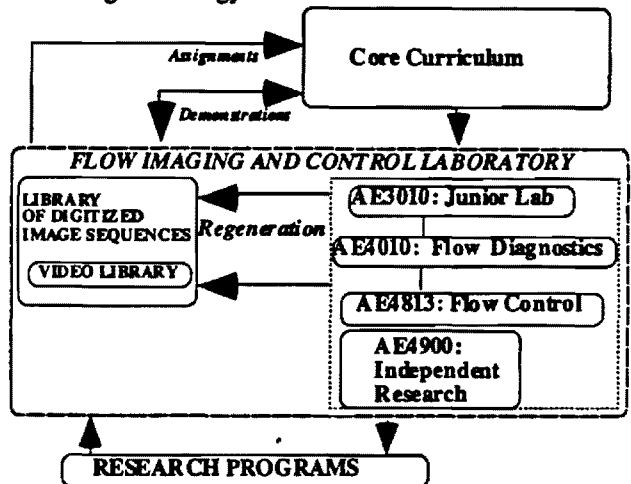


Figure 3: Information flow between the Flow Imaging and Control Laboratory, the Core Curriculum, and the Research Programs

Laboratory development

The existing facilities included:

1. a 42" x 42" low speed wind tunnel with a force balance, electronic pressure scanning, and Pitot-static probes,
2. a gas-burning pulsating combustor to measure periodic fluctuations in pressure and radiant light,
3. a 6" x 6" low-speed tunnel with a single-component laser velocimeter and hot-wire probes,
4. a smoke tunnel with model manipulator,
5. a PVC shock tube with pressure sensors and an oscilloscope with a Polaroid camera,

6. an indraft converging-diverging nozzle connected to a vacuum tank, and
7. a blow-down tunnel (Mach 2 in a 6" x 2" section) with a white-light schlieren system.

Capabilities added under NSF support are:

1. *Fiber-optic laser velocimeter and light sheet optics*: a 6-watt argon laser and integrated beamsplitter/frequency shifter in the 42" tunnel. Optical access to the test section has been modified, and the facility sealed off in three sections for laser safety.
2. *Water table*: this ancient device has been revived. It enables observation of unsteady flows. Water flows can be used to simulate supersonic wave phenomena. A video camera and PC convert this into a quantitative imaging facility.
3. *Image processing*: three Intel-486 based PCs are equipped with A/D, D/A, and frame-grabber boards with Digital Signal Processing chips. These enable hardware and software-based 2-dimensional FFT for image processing. The A/D and D/A enable control algorithms.
4. *Spatial correlation velocimeter*: this system converts video image pairs of flows into quantitative planar velocity fields. The computer systems described above are used for this.
5. *Smoke tunnel flow control experiment*: combining a frame-accurate video camera with the smoke tunnel has enabled such experiments as the dynamics of flows over turbine cascades.
5. *Shear layer control*: the existing helium-neon laser is used to generate light sheets to study the dynamics of seeded low-speed jets, as a prelude to controlling jet flows by external forcing.
6. *Hot-wire spectral analysis*: Time series analysis and PC-based A/D converters are used with the thermal anemometer in the 42" tunnel.
7. *Acoustic measurements*: the spectral analysis capability enables acoustic measurements using microphones. Acoustic drivers are also used.
8. *Bragg-cells*: An acousto-optic laser beam modulator is used to strobe laser illumination in synchronization with external events such as the acoustic drivers or hot-wire signals
9. *Videocameras*: Videocameras and editors combined with frame-grabbers and graphics software provide a powerful resource to capture fluid dynamics, correlated with the dynamics of complex objects. Time coding is used to obtain 133ms resolution. Separating frames into odd and even lines enables 17ms resolution. The videocameras provide shutter speeds upto 100µs.
10. *Software development systems*: include FORTRAN and C-language compilers.
11. *Multimedia Development System*: Three Macintosh Quadra systems (a 700, an 800CD, and an 840AV) with frame grabbers and various

dynamic image displays and software systems are used to develop image databases and problem sets. Two 3.5-inch optical drives enable interactive storage on 256MB or 128MB diskettes. The systems are connected through Ethernet to the School's local area network and hence to the flow facilities and the computer lab.

Development of the New Curriculum

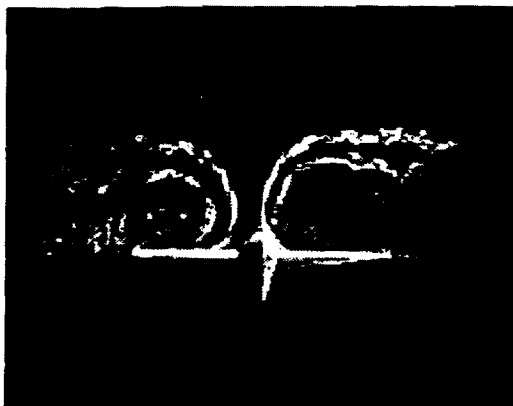
Given the constraints and resources, the approach consists of the following stages:

1. Link to the present core required curriculum
2. Find interested students
3. Create new course on flow diagnostics
4. Create new course on flow control
5. Get participation of other faculty and students
6. Create image database
7. Set up self-sustaining mechanisms
8. Develop changes to the existing curriculum
9. Identify characteristics of the new methods.
10. Get consensus on changing curriculum
11. Implement new curriculum in full
12. Maintain self-sustaining system.

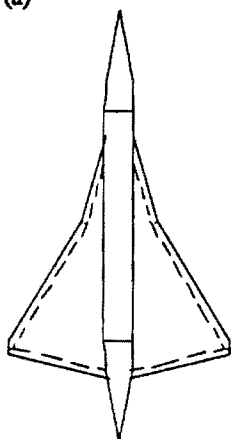
Each is considered below.

Link to the present curriculum

In the Fall of 1992, the students in AE 3010, the required junior lab course, were given a short lecture on aircraft aerodynamics at high angles of attack, and then asked to digitize video frames from a tape of laser sheet flow visualization over a generic wing-body. The first part of the tape (see Fig. 4a) showed the reality of asymmetric patterns, followed by efforts to obtain symmetry. The tape came from an undergraduate Special Problem⁵ as part of a NASA Langley research grant. In the symmetric-flow part, the aircraft model moved at constant speed through the laser sheet, with a clock on the tape linking each frame to the model position. The students had to use judgement to trace the trajectory of the center of the vortex pattern on each side of the model independently, from frames grabbed into an engineering graphics program. After some trouble with the idea of locating the center of a fuzzy pattern, the students were surprised to see the accuracy of their work when they plotted the digitized coordinates on plan and side views of the model. The success of this experiment became evident during the final presentations, when several students used strategies where the video camera and laser sheet were routine tools for measuring dynamics of various processes. This experiment has become a routine part of AE3010.



(a)



(b)

$\alpha = 25 \text{ deg.}$



(c)

Figure 4: a) Cross-flow laser sheet image of the asymmetric vortex flow over a wing-body configuration at angle of attack. (b) plan view of the model. (c) side view at 25 deg. incidence.

AE4010: Flow Diagnostics

In Winter '93, this course was developed and taught for the first time. The pre-requisite was AE3010 or some acceptable exposure to measurement techniques. The class of seniors and graduate students organized themselves into three teams. Each team set up one experiment:

1. Identification of noise sources in the 7'x9' tunnel using microphone cross-spectral analysis.
2. Instantaneous velocity fields in the water table using Spatial Correlation Velocimetry.

3. Correlation of periodic phenomena in the turbulent vortex flow over yawed wings in the 42" wind tunnel using spectral analysis.

Each team was asked to get their experiment working by the middle of the quarter, with a rudimentary instruction manual to go with it. During the rest of the quarter, the teams were to visit each other, using the experiments under the guidance of the development team. After a few general lectures, the rest of the "theory" was divided into 3 concurrent areas: 1) sensing techniques for pressure, velocity, temperature, density, and reaction rates and for visualizing unsteady phenomena, 2) digital signal processing and statistical analyses, and 3) flow imaging for quantitative multi-dimensional diagnostics. This allowed the students to learn the science behind all three major experiments in a timely manner. The students also learned from the graduate research teams, and in practice there was a great deal of interaction between the three teams throughout the quarter.

As expected, the experience of preparing these experiments was frustrating. Hardware and software problems plagued the data acquisition systems. The results were often ambiguous. However, by the end of the quarter, the manuals were written and refined based on user experience, each student had used every experiment, the theory learned in the class had been put to immediate and successful use, and the teams made excellent presentations of the experiments that they had developed. Student suggestions improved the experiments. The results of the anonymous evaluations at the end of the quarter were very encouraging: *the opportunity to develop new experiments and participate, instead of just watching or operating, was seen as a welcome change by the students.* A new experimental course had thus been successfully developed and taught without having pre-written instruction manuals, ready-made and perfect experiments, or experienced teaching assistants.

AE4813: Flow Control Techniques

In the Spring of 1993, a new course was developed and taught on the topic of flow control. It was made clear that the instructor would be learning the subject along with the students. Again, the students started team-development of four experiments:

1. spanwise blowing control of flow separation on a rolling delta wing
2. acoustic modification of shear layers
3. modification of stall in a blade row
4. modification of cavity flow oscillations.

The lectures covered flow separation phenomena^{6,7} in detail, and went on to discuss turbulence control, acoustic interaction with shear layers, vortex flow control on wings, and control of combustion instabilities. A literature search was performed on the subject of flow control, and students were given the option of selecting one or two papers to review and present for discussion in class. The subjects were diverse, including numerical simulation of vortical structures in turbulent boundary layers, modification of delta-wing vortex flows, drag reduction on cylinders, experiments with compliant surfaces, and suppression of turbomachine instabilities. Again, this experiment was a success: the student reviewers did an exceptionally thorough job of preparation. Since the presenters were students (with the instructor participating), the attention, participation, and comprehension level of the class in these presentations was far above anything the instructor could have achieved, lecturing alone on the same subjects. In addition, the class was invited to tour the acoustic flow control facilities at the Georgia Tech Research Institute, with Professor K.K. Ahuja returning with a lecture explaining these techniques. The efforts to get the flow control experiments were less than 100% successful, though it should be noted that without the help of the students who had already taken AE4010, the experiments would have been quite hopeless. Once again, the student evaluations were extremely forgiving of this aspect, and expressed satisfaction at what they had gained from the course.

Recruits into the research program

Bringing undergraduates into the research programs is an integral part of the project. This is the most efficient way for a research university to provide opportunities for professional problem-solving experience within a highly motivated and disciplined mentor team of graduate students. A grant from the Georgia Tech Foundation enabled support of 12 undergraduates for various parts of the year as assistants in the course development and associated research. A unique feature is that these full-time students must fit their working hours into their course schedules of 15 to 17 credit-hours.

Video database

The central resource of the project is the video image database. This has been set up on 256MB optical diskettes using the Apple HyperCard and Quicktime software. An interactive data base provides a catalog of image sequences available on a library of videotapes.

Each tape reference contains short dynamic sequences which the user can use for browsing, or save into other graphics programs for analysis. Once the tapes are retrieved from the library, desired portions can be digitized through a video player and frame grabbers on the Quadra computers. In subsequent stages, selected image sequences stored on diskettes are to be combined using multimedia tools for use with problem sets and classroom demonstrations.

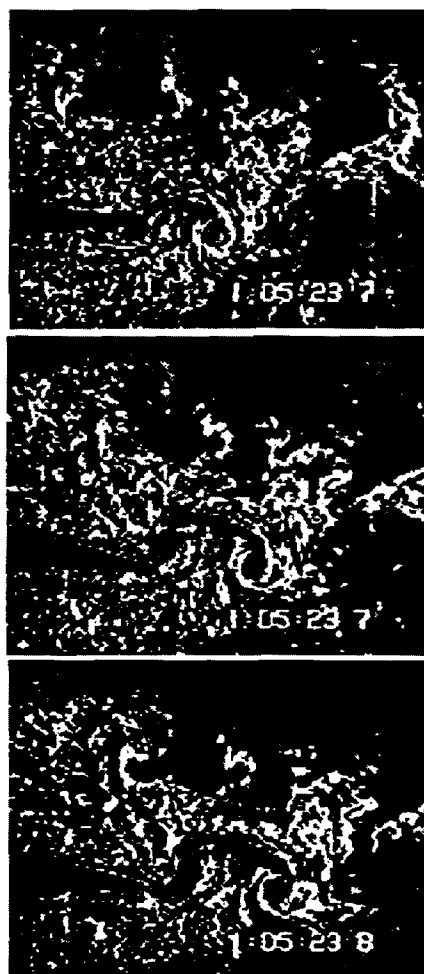


Figure 5: Three successive frames of video from laser sheet visualization of the wake developing behind midspan of an oscillating wing in the wind tunnel.

An example is the oscillating-airfoil sequence shown in Fig. 5. The images were acquired by videotaping smoke illuminated by a pulsed laser sheet at midspan of a high-aspect-ratio wing oscillating in the 7' x 9' wind tunnel. This is as close to "hands-on" as anyone can get in this experiment. Due to laser safety considerations, the experiment can only be

observed through a video camera. The airfoil angle of attack can be measured accurately by taking each image into a computer graphics program such as Deneba Canvas™. A time-coded copy of the tape makes it precise to 1/30 second. The airfoil dimensions are known, so that the distance to the centers of vortex structures downstream can be measured. The change in the bound circulation of the airfoil can be related to the strength of each vortex structure approximately; this in turn can be used to analyze the vortex motion.

Another example is the cylinder wake shown in Fig. 6. Here chalk dust floating on the surface of the water table has been captured on videotape. The static images convey little information. A Quicktime™ video clip of 320x240, 8-bit pixels was captured at 27 frames per second on a Macintosh Quadra 840AV. Shedding frequencies and fluctuation amplitudes of streamlines can be measured from the video in slow motion, or from the digitized clips using graphics programs. Using the Spatial Correlation Velocimetry procedure, successive frames from this tape can be analyzed on an i486 PC to give instantaneous velocities in the wake, as shown in Fig. 7. The difference from conventional textbook practices is that the student can observe the actual behavior of the flow, and then get real numbers from the flow. Once the technique was learned in AE4010, the students in AE4813 used the technique to conduct studies of flows around complex configurations, e.g., Fig. 8.

This demonstrates that abstract mathematical techniques become routine tools once the students have a mechanism to see their utility, test hypotheses, and use the methods in a non-threatening environment. All of these experiments took a long time to develop. In many cases, the development time could have been greatly shortened by the intervention of the instructor at the expense of the learning experience. In others, new methods were discovered. For example, the users of the SCV method forgot strict instructions to keep the camera shutter exposure short to avoid streaking in the images. As it turned, this enabled excellent results in the recirculating flow behind the cylinder. In retrospect, it became evident to the instructor that there was no reason to keep the shutter exposure short at all, since the streaks would correlate very well between consecutive video frames. This was a major advance in the capability of the technique

A third example is the sequence shown in Fig. 9. Here we see video frames acquired during the start-up of a supersonic wind tunnel, with density gradients visualized using white-light schlieren. In Fig. 9(a), the normal shock has not yet been fully "swallowed" through the test section. By measuring shock angles, it is possible to estimate the Mach number distribution in the test section. Elsewhere on the same tape is a curious sequence of what happens when water comes down the test section: this provides food for thought to the instructor, but is not yet understood well enough.

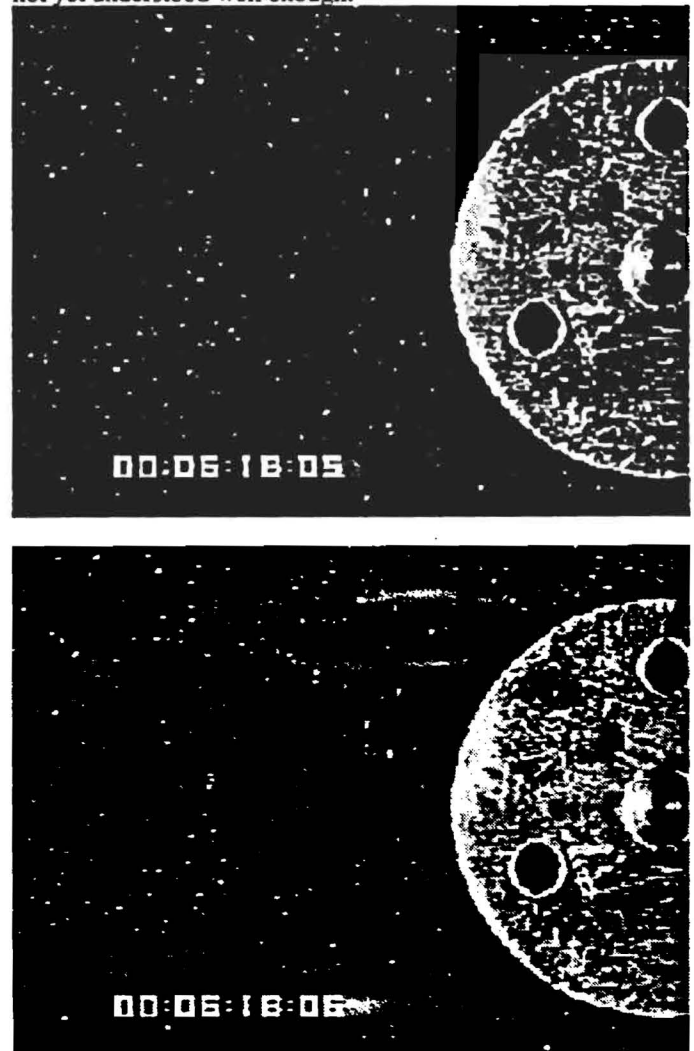


Figure 6: QuickTime™ digitized video frames of chalk dust in the wake of a cylinder in the water table. The freestream is from right to left.

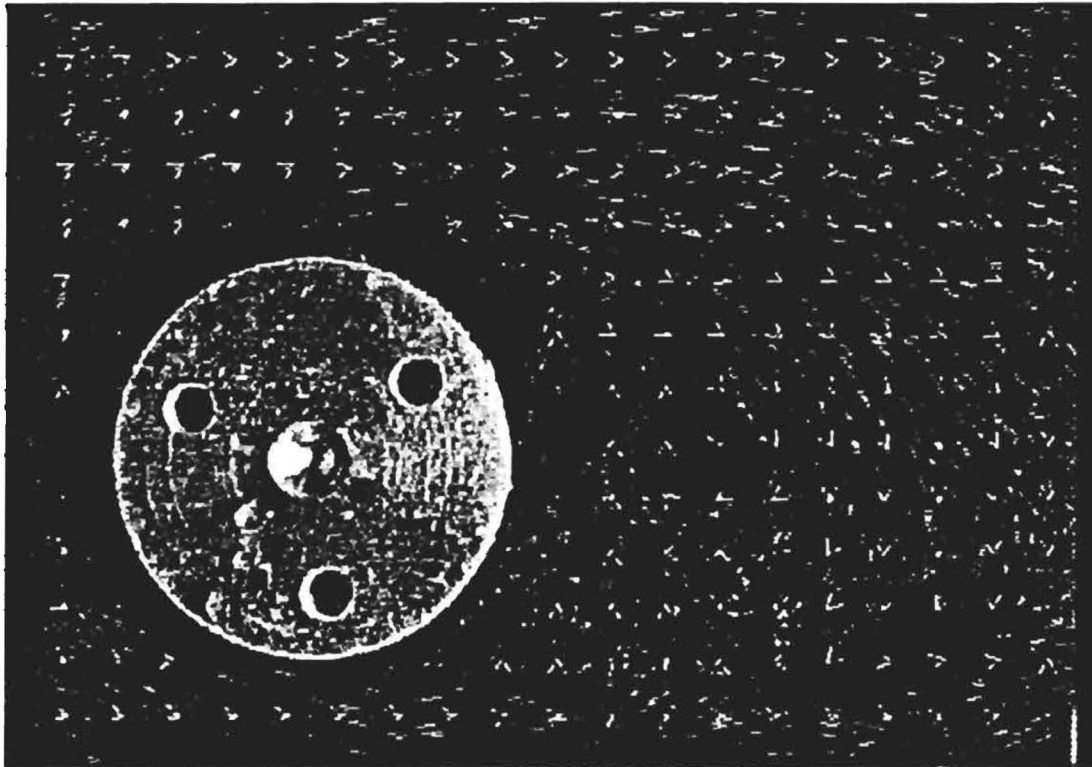


Figure 7: Velocity vectors computed using SCV in the wake of a cylinder in the water table. Freestream is from left to right. From Ref. 8.

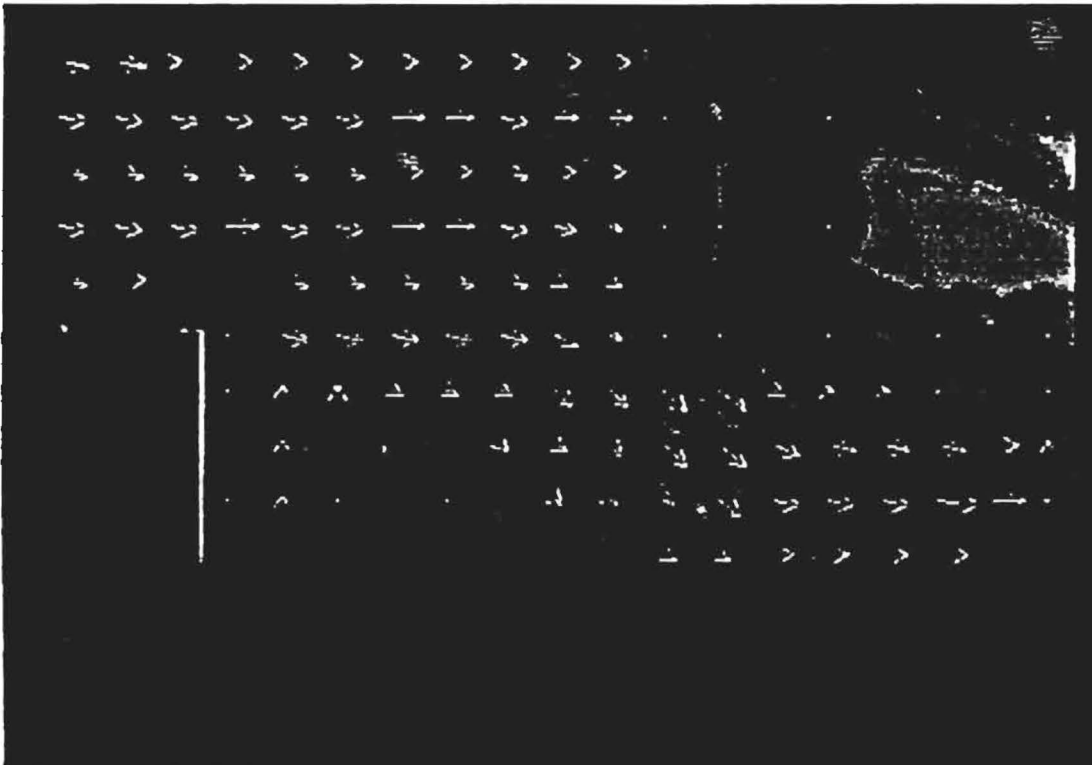
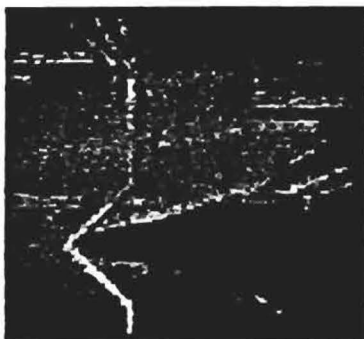
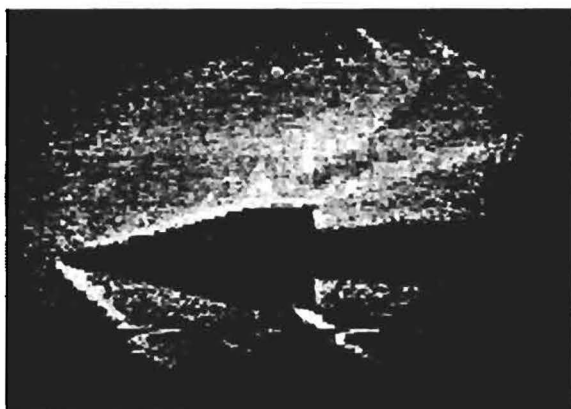


Figure 8: Velocity vectors computed using SCV over a complex configuration. Freestream is from left to right. From Ref. 9.



(a)



(b)

Figure 9: Video frames captured during the startup of a supersonic tunnel. (a) before the flow is fully supersonic in the test section, and (b) supersonic, with wave reflections from walls.



Figure 10: Model used for initial studies of stall propagation in blade rows in the smoke tunnel.

It should be pointed out that the experimental set-ups themselves are not necessarily sophisticated. An example of a preliminary test object is the "blade row" shown in Fig. 10, used for flow visualization in the smoke tunnel. It consisted of pieces of plastic

window blinds, attached to two bars whose relative motion changed the angle of attack. Simple as it was, the streamline patterns and dynamics through this device yielded some valuable information to the careful observer.

Regeneration

The key to the long-term success of this effort is an efficient mechanism for improving course material and expanding the resource library without continued external support. This process has started. Figs. 6 through 8 came from student work in AE 4010 and 4813. The experiments have been videotaped for the database.

Expansion

The program has expanded to bring in other faculty with expertise in acoustics and combustion. The multimedia equipment and software decisions are coordinated with faculty involved in the SUCCEED coalition of universities attempting to revolutionize undergraduate education. This provides a way to disseminate generated course material more extensively through CDs and other media.

CONCLUDING REMARKS

We have thus completed one cycle of the iteration through Stage 7 of the project. As the second cycle of the iteration shown in Fig. 3 begins, there are several tested experiments from last year, in addition to the new capabilities that have come on line this Summer and Fall. A new vertical-flow unsteady water tunnel is under construction. Image-based problem sets are also under development. These will be tried out in the second cycle. Meanwhile, Stage 8 is starting with the results of the new courses being integrated into the core curriculum.

The linkage between the different portions of the experimental curriculum is illustrated in Fig. 3. The basic exposure to experimental techniques and laboratory practices gained in AE3010 enables the student to start using the advanced tools of AE4010, the Diagnostics course. In turn, this experience is immediately put to use in the Flow Control course, with each student team containing at least one student veteran of AE4010. The courses have the obvious intent of recruiting some students into research programs using independent Special Problems. All of these courses provide additional material to be incorporated into the image database and thence into problem-solving.

The objectives laid out in Ref. 4 have proved to be achievable. The surprise has been

that assistance and intellectual contributions from students has far exceeded the conservative design planning of Ref. 4. Supportive evidence for the hypothesis of improved learning efficiency comes from all three courses taught under this scheme to-date. The students who analyzed vortex trajectories in AE3010 had never had a theoretical lecture on vortex-dominated flows, nor indeed any occasion to consider even swept wings. The students who presented summaries of turbulence simulation papers in AE4813 ventured far from what they were supposed to have learned. The instructor in any conventional curriculum would have been unable to introduce even the concept of these papers in a one-way information transmittal. In the relaxed setting of the student presentations, after the students had gone through one iteration of struggling with the papers, these concepts were easily conveyed through discussion, and set in terms that the students understood. Diagnostic tools which were developed as research items have quickly become routine tools in the undergraduate's repertoire. It is emphasized in closing that the entire progress to-date has been made through the efforts of a constantly-changing team of undergraduates, with some help from graduate students. A strong bridge has been built between the undergraduate curriculum and the research program.

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IMAGE PROCESSING IN THE UNDERGRADUATE FLUID DYNAMICS LABORATORY

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ABSTRACT

Easy access to video imaging, digital frame grabbing and image processing technology has opened up exciting opportunities in fluid mechanics education. This paper presents several examples of student work, and discusses new curricula based on these new developments. Complex, unsteady flows can now be quantified using multi-dimensional techniques. Image sequences can be stored and used in problem-solving. The author extrapolates these experiences to the hypothesis that image-based curricula can revolutionize fluid dynamics education, and permit the undergraduate to become familiar with fluids engineering technology, exploiting unsteady flows.

INTRODUCTION

In the hectic environment of a modern engineering school, it is difficult to conduct laboratory experiments suitable for hands-on participation by large classes. Advances in computational capabilities have created the demand for (and the relatively easy solution of providing) increased attention to computational fluid dynamics. At the same time, the time available to teach fluid dynamics is compressed by demands for "broader" curricula, advances in other fields, and the pressure to reduce the total hours required for the first degree. The laboratory course is an easy candidate for cuts, as Shop classes were in the past. There are two undesirable results:

- 1) The typical undergraduate gets very little exposure to the beauty, variety, and realities of fluid dynamics, instead seeing a collection of smart techniques for solving differential equations "governing" steady, laminar, attached, single-component flows of perfect gases over streamlined shapes. Sometimes this occurs at the expense of physical insight, and of students who might otherwise become intuitive leaders in fluid dynamics.
- 2) Prevalent opinion holds that the future is all in CFD, and that hardware experiments, if done at all, are purely for "code validation", with attention restricted to those phenomena which are already known and modeled in the codes.

The popularity of the CFD revolution is partly because it allows everyone to participate actively in studying

flows. High-tech experimental facilities lack the open access and user-friendliness of the computer. This need not mean that their products should remain inaccessible: the video camera and the image processing board in a personal computer have opened the way for all of us to see, analyze, and explore ideas for modification of flow phenomena without ever going near a laser, by working with image sequences. The image sequences themselves may be acquired behind closed doors. This can help re-think and re-design our entire approach to fluid dynamics. Such a change is sorely needed. Except for computational methods, the content of undergraduate textbooks appears to be stuck where it was when today's senior professors were undergraduates. Complacent that "the fundamentals remain the same", we have perhaps allowed the frontiers to pass us by, and the gap between graduate research and undergraduate education to widen beyond leaping distance.

The experience of seeing and comprehending the realities of fluid flow is crucial to interest, innovation and problem-solving in flow analysis and flow control. Ideally, experiments must explore what is not computable or even suspected, and lead advances in fluid dynamics. Without the ability to do this, there is a clear danger that our graduates of tomorrow will be reduced to being mere operators of huge and complex "black box" computer codes, totally at the mercy of the admirable few who write such codes.

OBJECTIVES

This paper describes a tentative experiment to try to help this situation. We hope to:

- a) bring the *dynamics* of flows into the curriculum and the problem-solving process using digital image processing,
 - b) enable flow-control experiments, and
 - c) enable students to try independent experimental projects.
- These efforts aim to give the engineering graduate the comprehension, experience, and confidence to use advanced concepts and techniques in fluids engineering.

Why should our curricula improve?

Fluid mechanics has moved into an era where multi-dimensional, unsteady multiphase flows must be controlled for useful purposes. High-lift devices, artificial hearts, cryogenic turbines, fluidic cutting tools, fluid bearings, and techniques for drag reduction, noise cancellation, mixing enhancement, and vibration control are becoming common parts of engineering practice. The teacher at the undergraduate level faces an uphill task, if the starting

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point for most fluid dynamics curricula still stays stuck at the steady, laminar, incompressible, single-phase, irrotational level. Very few real-life flow problems are solved using the Laplace equation. We must seek new ways to get the student more efficiently to the leading edge of technology while still mastering the theoretical discipline needed to become a versatile problem-solver and innovator. Chalkboard-textbook techniques are simply not enough.

The objectives of a curriculum revision are non-controversial: we all want to achieve vast improvements in

- 1) the percentage of what we teach that our students actually comprehend
- 2) the success rate of all of our students
- 3) their ability to apply what they learn to solve new engineering problems
- 4) our ability to carry our courses to the very edge of technology and a little beyond.

Of course, these must be achieved with no increase in our workloads, and with an increase in our ability to work individually with each student. Whatever solution we attempt must fit within all of our current constraints.

The state-of-the-art

In the laboratory, detailed dynamics of flows can be captured, at least on a model scale, using visualization techniques. Pulsed or strobed lasers and fast-shutter video (the latter available on most home camcorders) can "freeze" practically any time scale of motion, and tomographic and holographic techniques enable 3-D quantitative imaging. The dynamics of vortex pairing, shear layer instability, acoustics-turbulence energy exchange, and flow-induced vibrations can be captured, quantified, and tailored. Flows can be made to do things that defy many of the "limits" taught in the steady-flow class-room (e.g., maximum lift coefficient, diffuser divergence angle). Digital feedback control offers the potential to carry these abilities much further, if only one can be sure of exactly what to control. With "smart materials", flows can be made to do what we want, on an instantaneous basis. Even with all these, we have just begun to get our toes wet: whole oceans of possibilities are opening up in fluids engineering.

THE PRESENT CURRICULUM

The undergraduate fluid dynamics curriculum at Georgia Tech's School of Aerospace Engineering begins with AE3003, which introduces potential flow theory and analyses, going on to the steady incompressible aerodynamics of airfoils and unswept finite wings. AE3004 covers compressible flows, enabling quasi-1-d analysis of nozzle flows, moving shocks, supersonic tunnel starting problems, flows with friction and heat addition, and going on to oblique shocks, Prandtl-Meyer expansions, and nozzle exit flows. AE3005 teaches analyses of viscous flows, concentrating on boundary layer approximations of the Navier-Stokes equations. AE4001 teaches linearized analyses of high-speed aerodynamics. Beyond the core, interested students choose from a range of advanced elective courses on

computational fluid dynamics, combustion, hypersonics, viscous flow, and rotor aerodynamics.

The only laboratory course in the core curriculum is the 2-quarter-credit-hour AE3010, which serves many purposes. Groups of 3 to 5 students operate a series of eight experiments:

1. Force and moment measurement on a finite wing in a 42" square-section low-speed wind tunnel, with flap deflection, end-plate effects, and angle-of-attack variations included. The balance requires calculation of interactions between components, and a careful analysis of error bounds.
- 2a) A survey of the boundary layer of the wind tunnel and the wake of a full-span wing using a flattened Pitot probe, combined with measurements of the pressure distributions on the wing using a Scanivalve pressure switch and a Baratron transducer.
- 2(b) Visualization of flow patterns over a variety of shapes in a smoke tunnel, with provisions for rotating the models.
3. Hot-film anemometer survey of the wake of an airfoil in a 6" x 6" wind tunnel, where the students must calibrate the probe, decide on traverse resolution, and keep track of signal amplitude and amplifier and filter settings on the data acquisition system. Only mean and root-mean-square values are computed, going across the wake.
4. A survey of the turbulence profile across a round jet inside the 6" tunnel using a single-component, forward-scattering laser Doppler velocimeter. Histograms are used to compute mean and rms values.
5. An unsteady combustion experiment, where a Rijke-type vertical pulse combustor is used to demonstrate resonance phenomena involving acoustics and heat release, and phase relationships between pressure and flame radiation.
(note: experiments 1 - 5 use a PC-based A/D converter and digital data acquisition system with menu-driven user interfaces)
6. A shock tube experiment, where transient shock properties are captured on Polaroid film using an oscilloscope and pressure sensors.
7. An indraft nozzle exhausting to a vacuum tank, where nozzle pressure distributions are measured using a bank of manometers and a pitot tube, and used to study shock locations.
8. A blow-down supersonic tunnel, where a schlieren system is used to visualize shocks and expansions.

The labs are run by two carefully-selected first-year graduate students, with minimal supervision needed from the instructors. Each experiment is accompanied by a set of questions whose answers must generally be found from the experiment. The reports on the experiments, which each student must write independently, introduce publication formats. The grading takes note of the rate of improvement of lab reports. At the end of the course, each student is assigned a hypothetical problem where a measurement solution must be designed to meet specified criteria. The problem may involve measuring anything from reaction kinetics in home heaters or supersonic combustors to flows

through roof-top ventilators or over swiveling advertising signs. The six-minute presentation followed by questions tests the student's preparation and thought. The results are often amazing, both in innovative spirit and in thoroughness. Obviously, some students find the workload, as in the other lab courses in Structures and Controls, disproportionate for a 2-credit course, and this is the topic of complaints on the anonymous course evaluations. On the positive side, student performance on this course is far above the average, and there is no indication that performance on other courses suffers as a result of the workload. In fact the demand for efficient completion of high-quality work pays off in their performance in later courses. Nine quarters of this exhilarating experience have convinced the author that the traditional courses, where our students sit quietly and copy down equations from the chalkboard to survive written tests, do not even begin to tap their true potential.

No doubt this can be argued to be a state-of-the-art curriculum. The fact remains that we have little time to let the students see the beauty and variety of unsteady fluid phenomena, and to learn how to control flow phenomena.

THE CONCEPT OF AN IMAGE-BASED CURRICULUM

Now let us imagine the following situation for a moment, from the student's perspective:

In the first course in fluid dynamics, the instructor calls up real sequences of flow images, both in isolation and in dynamic sequence, to explain concepts, assumptions, and approaches. Back in the dormitory, flow images can be brought up on computer screens using diskettes, with the sequence of images showing what the flow will really do. One can measure instantaneous velocity vectors, vorticity contours, vortex trajectories, and pressure distributions from the images. The homework assignments demand solution by going over the images carefully, observing, analyzing, and correlating facts with the theory learned in the classroom. Eventually one learns to figure out and use simplifying assumptions. As one moves deeper into the curriculum, the assignments become more complex, and require more analysis, engineering judgement, improvisation, and bold hypotheses.

Seeing and struggling with such images through several courses, the "average" student completes the core curriculum with the same (or better) level of experience of seeing flow behavior as the experts of today. The common misconceptions of today's graduates could be reduced, and the overall level of comprehension greatly improved. On the other hand, the theoretical analyses which must now be hammered into somnolent students on the "*learn this now; you'll be glad you did later*" basis, can be introduced as useful tools from the beginning, and fluid mechanics may no longer be feared as a subject which is all differential equations and not much fun.

Our experiment is to see how to implement such a curriculum. The clear intent is to *increase* the theoretical rigor and complexity, but to make this feasible and palatable using advanced tools. Once such a system is in place, the sequence of topics in the curriculum can be rearranged in many ways; several items which are now "indispensable" can be deleted to make room for new knowledge. The restricted, approximate, analysis techniques can be taught as what they are, not as the gospel of fluid dynamics. Alternative approaches can be explored. At the same time, the student's experience of seeing images generated using modern experimental techniques can increase interest in experimental work, and in methods for actively controlling flow phenomena. It will emphasize that fluid phenomena can be diagnosed, isolated, extracted, analyzed and controlled.

Previous Work

The NSF Workshop on Fluid Mechanics¹ in Fall '86 emphasized the usability of Fluids technology and identified shortcomings in current curricula. The opportunity to design more integrated learning methods is being recognized. Beasley, Culkowski, and Gufner² describe integration of laboratory, lecture, and office space, where students use full-scale equipment to quickly test out what they learn in the classroom. This recognizes the advantages of "learning on the job", a concept similar to what is advocated here. Lamancusa³ reports on a laboratory aimed at giving mechanical engineering students an integrated look at electronics and computer interfacing.

Alam, Bakos, and O'Leary⁴ explore the opportunities offered by new video and computer technology in designing an "Image Database", an "instructional picture database" for a pavement design class. They used PC-type computers, with an optical disk drive and image capture and video systems. They explored the requirements of storage, transmittal, retrieval, and usage. Van Valkenburg⁵ advocates "tutored video instruction" as the preferred mode of teaching of the future, as a superior alternative to large-group lectures. Again, the opportunities presented by the high-speed workstation as a semi-intelligent information source are recognized. Greenfield⁶ discusses the impact of new CD-ROM technology on Integrated Learning Systems.

Relation to Present Work

The curriculum discussed here uses technological capabilities similar to what is advocated by these educators. Here, the computer serves two purposes:

- a) *it enables comprehension of dynamic processes.*
- b) *it enables precise analysis of dynamic features, and the extraction of desired information.*

The learning enhancement comes from first-hand experience of working with actual fluid flows on the one hand, and by extensive use of modern diagnostic techniques on the other. The improved capability comes from an accelerated learning path, which makes students comfortable with fluid dynamics earlier, so that they can go on to experiment with flow control techniques with a solid theoretical and practical

background. Improved comprehension comes from the opportunity for "iterative learning"; improved performance comes from the opportunity for continuous improvement.

A MODEL LABORATORY FOR THE FUTURE UNDERGRADUATE CURRICULUM

The place of the planned Flow Imaging and Control Laboratory in the curriculum is shown in Fig. 1. The laboratory will first produce dynamic image sequences on selected flows. These will be used to create computer-based data sets accessible to the student. The core courses (AE3003-4-5, 4001) will use dynamic image sequences to illustrate such concepts as vortices, streamlines, rotational vs. irrotational flows, circulation, boundary layer transition, shear layer formation, mixing, and dissipation, and shock formation. Image sequences will be used in problem sets, along with user-friendly digital image analysis routines, to actually compute flow quantities. Velocity fields will be calculated from image pairs, as will circulation, vorticity contours, shear, and dilatation. Lift coefficients will be calculated directly from these, and compared with theoretical and measured values. The detailed starting process of a supersonic wind tunnel will be studied, revealing the mysteries of the "starting problem", "shock reflections", and the relation of shock angle to Mach number. The starting of a jet and a pipe flow will be examined, and the detailed structure of a supersonic jet will be seen. The added physical insight will reduce the incidence of common theoretical misconceptions, and, hopefully, light up the student's curiosity and imagination.

The laboratory will be organized around the strengths of the present undergraduate fluid dynamics laboratory. The new ingredient will be the flow visualization, the addition of experiments on unsteady flow processes, the image acquisition, and the image analysis capabilities.

To the student who comes out of these courses, laser-based flow visualization and digital image processing will already have become "common practice", just as word processors and spread-sheets are now. The junior lab, AE3010, will give the student broad experience in actually conducting such experiments. A few of these students will take AE4010, the Advanced Diagnostics course, where advanced techniques will be taught with much greater rigor, and more challenging experiments will be attempted.

In AE4011, the Flow Control Elective, the projects will challenge the students to achieve desired objectives using tools such as acoustic excitation, mechanical flaps, edge modification, and surface tripping. The diagnostic techniques from AE3010 and 4010, combined with the theory of the other courses, will be integrated here to do what the engineer enjoys most: learn to control and improve useful devices and processes. A precious few will take up AE4900 Special Problems for independent research. The cycle is completed when the best experimentally-observed

images are compiled and converted to demonstrations and problem-sets for the core courses. This is the mechanism for constantly advancing the curriculum. In brief, AE3010 will show students the beauty and complexity of fluid dynamics, as well as the bases for analytical methods. AE4010 will teach diagnostic techniques, and AE4011 will teach what is known about flow control. All courses will insist on careful observation, and use the question "why?" to demand careful interpretation. AE4010 and 4011 will teach "how". AE4900 will teach exploration of the unknown using tested facts, complemented by analytical and extrapolative reasoning.

New Features

What is new is that the student will learn by working with *actual flow problems* throughout the curriculum. The image sequences will try to tell the student "what will the flow really do" while posing questions that take intense analytical reasoning, justified by numerical results. (Can you assume that this is steady? Is that a vortex forming? How strong is it? Is this flow approximately irrotational? Let's try looking at vorticity contours. How turbulent is this flow? Is there substantial momentum transfer across the dominant flow direction? Is that shock steady? If not, why not?) Secondly, they will *get used to applying* numerical techniques from the beginning (image analysis must use finite differences, interpolation, and numerical integration), so that the CFD teacher can teach more. Thirdly, the student can take home the "correct answer" in the form of flow images on diskettes, and try out a variety of solution approaches. Finally, these techniques allow for iterative learning, where one gets to improve one's comprehension of the subject matter through several cycles with no penalty for imaginative attempts. These are the ingredients needed for fast learning and development.

Progress To-date

Over the past seven years, we have observed the progress of over 25 Undergraduate Special Problem projects at the Aerodynamics research laboratories. These students have, over periods of one to two quarters, when they were typically taking 3 other courses, become valuable members of research teams, adept at flow visualization techniques. Their insight into fluid dynamics increased dramatically, as did their grades in subsequent courses.

Over the past three years, as planning for the new experiment has become more focused, several projects have served as test cases (Refs. 7-11). Recent studies of vortex flow over aircraft at high angles of attack, a rotor wake in forward flight, and vortex shedding from objects of complex shape have all used digital processing of flow images to extract quantitative information. Additional data points are the "independent proposal" presentations at the end of the AE3010 lab course each quarter: these have been real eye-openers on what the junior-level student can do.

Proof-of-Concept, 1990-91

In 1990-91, two junior-level students were recruited into research projects, to work on image-related problems. One became the vortex trajectory expert on a NASA Grant studying unsteady vortex flow over an aircraft at high angles of attack. The other researched, designed, and analyzed the image data from a continuing industry-sponsored project on vortex shedding from complex-shaped objects, correlating image-measured shedding frequencies and flow structures with hot-wire spectral results. We have been through the mechanics of acquiring, storing, transferring, analyzing, and reporting on the images. Neither student had taken any course on the various problems encountered, but over the course of a quarter, with little formal lecturing, each became superbly competent at his work, and in the process learned a great deal about everything else that was being done in the research labs. Each of these junior-level student projects resulted in a very significant improvement in our capabilities at the John Harper wind tunnel.

Implementation Plan: Video-Based Image Analysis

The key is the easy availability of accurate video camcorders, inexpensive frame grabbers and digitizing boards for personal computers, and the advent of the 1.44MB diskette, which permits storage of several 8-bit digitized images. These permit capture of flow images acquired in the "inaccessible" research laboratories for convenient analysis on small computers, and for wide dissemination. We are putting together a "library" of video image sequences. Samples from such a sequence are shown in Fig. 2. The development of the wake of an oscillating airfoil is shown, along with a wide-angle view of the wake. The double exposure apparent in the image is an artifact of the digitizing, and allows the odd and even video lines from two consecutive frames to be separated using a computer program. This is just an easy way to grab two consecutive frames. Another similar sequence has been acquired on natural vortex shedding from a cylinder, where the Strouhal frequency can be easily calculated from the images. Other images are discussed later in the paper.

EXAMPLES OF IMAGE SEQUENCES AND ANALYSES

The range of possibilities is unlimited. Here some examples are given, based on recent work at the author's laboratories.

Vortex Flow Over an Aircraft Model

Figure 3 shows the asymmetric vortex flow over a generic wing-body model, caused by forebody instability. This frame is from a sequence of vortex flow patterns recorded as the model moved slowly through the laser light sheet¹⁰. The asymmetry was traced to the nose and solved by passive geometric correction. Vortex trajectories then digitized from the symmetric-flow videotape are shown in Fig. 4. Recently, Griffis¹¹ has attempted to correlate the ensemble-averaged, digitized image intensity distribution

from the seeding pattern with the velocity field, and has obtained some preliminary success.

Wide-Field Shadowgraphy

Truett¹² obtained wide-field shadowgraph images, frozen with 25-nanosecond resolution with a copper vapor laser, documenting the density gradients in the wake of a helicopter rotor. In the actual experiment, the research challenge was to stretch the technique to low Mach numbers, and some success was obtained even with rotor tip Mach numbers as low as 0.28. Later experiments were conducted with a hair dryer with much better success. This is a simple experiment to conduct and record, as long as there is a density gradient to observe. Future challenges will be in extracting actual density fields from the gradient images using image processing algorithms.

Karman Vortex Street

Griffis¹¹ used images of a vortex street downstream of a round pipe, illuminated with a copper vapor laser sheet. He then compared frequencies computed two ways: first directly from the images, assuming that the vortex convection speed was the same as the freestream speed, and then by direct measurement of the spectral peak using time-series analysis of a hot-film anemometer signal. The difference provided a good means of calculating the convection speed of vortex centers, while seeing what causes the spectral peaks. This project led the student to investigate differences in shedding characteristics between objects of various shapes, as part of an industry-sponsored project.

The Roll-up of the Edge of a Vortex Sheet

Figure 5 (Ref. 13) shows the edge of the wake of a helicopter rotor, where the tip vortex core trajectory is seen to be modified by the roll-up of the inboard vortex sheet into a discrete structure. The associated phase-resolved velocity field is also shown, with the opposite signs of vorticity of the two structures evident.

Vortex-Induced Flow Separation

Figure 6 (Ref. 14) shows a newly-discovered result: when the vortices from a helicopter rotor interact with the flow over a wing at moderate angle of attack, massive flow separation results. This can be easily explained once one sees it happening, but shows the very large difference between what one would compute from "uniform downflow" rotor wake models, and reality. Again, sequences showing different phases of the interaction are on videotape, correlated with time indices.

ANALYSIS TECHNIQUES

As seen from the vortex tracking problems and the intensity correlation problems above, digital image analysis is an active and growing capability. These are performed on the Macintosh II computers in the School's computer labs, or on 80486-33MHz computers in the wind tunnel control room. As such, they are commonly-available and

inexpensive capabilities. Other examples of analyses are given below:

Starting of a Supersonic Tunnel

Figure 7 shows two frames from a sequence taken during the starting of our blowdown supersonic tunnel. A color schlieren system was used. As a preliminary example of quantitative analysis, we attempted to get instantaneous Mach number at various points using the local inclination of weak disturbances. The images during starting have several zones of supersonic and subsonic flows, and as usual with such problems, we quickly found ourselves wondering about the several features which were observed.

Velocity Extraction from Video Images

Our recently-developed capability to perform Spatial Correlation Velocimetry (SCV) has opened new doors in quantifying flow images. We are now able to extract two components of the instantaneous velocity vector at several points in a plane using two consecutive video images (or even by odd-even decomposition of a dual-exposed video frame). Examples are discussed below.

Stalled Airfoil in a Water Table

Figure 8(a) shows the pattern created by chalk dust sprinkled on the surface of water flowing around a small plexiglass model of an airfoil in our undergraduate laboratory. Fig. 8 (b) shows the velocity vectors computed from these video images using a 16-MHz Macintosh II¹⁵. Similar results are easily obtained for flows around cylinders and other objects, with a sequence of such plots showing unsteady phenomena.

Plunging Wing and Wing-Canard Interaction

Figure 9 shows samples from a video animation of velocity fields measured when an NACA0012 wing executed large-amplitude, arbitrary plunging motion in our large wind tunnel¹⁶. In this case, the experiment required powerful illumination, but the videotape, once obtained, can be transferred to undergraduate classes for analysis. Another example of velocity field analysis is shown in Fig. 10. Here, a sophisticated dual-intensified camera system is used to capture the flow patterns over a wing-canard configuration in close interaction¹⁷. The canard moves to various positions relative to the wing, causing effects which are clearly visible on the videotape. Again, the computation of velocity vectors (Fig. 10a) shows the complex flowfield. Fig. 10b shows the instantaneous velocity profile above the wing, showing the jet-like flow coming between the canard trailing edge and the wing surface.

Cloud Motion

A final example of such velocity measurement and flow analysis is the recent work of Goodson¹⁸, who used the video camera and computer to study the motion of clouds on a warm Spring day. Again, this was part of an undergraduate Special Problem project, and required no lasers

or wind tunnels to observe unsteady fluid mechanics on a grand scale.

As mentioned at the beginning of this section, there are no limits to the possibilities opened up by the video camera, with its 30Hz time resolution, freeze-frame options, and a computer with a digitizing board. Recent developments such as liquid crystal stress diagnostics and pressure-sensitive paints open up other possibilities similar to the velocity field measurement shown above. On a much simpler scale, a determined experimenter with quick reflexes and a sure hand can capture the detailed unsteady aerodynamics and vehicle dynamics of a bird or insect in maneuvering flight, and perform very quantitative analyses. The author recently had occasion to dissuade a young high-school scientist from her plans to stick pins into live butterflies in order to observe and revolutionize wing design: a butterfly in free flight would provide a much more useful test case, with the data capture being accomplished using a videocamera instead of less benign means. The results are awaited.

SUMMARY

The examples presented above are meant to trigger new thinking. The video camcorder, digitizing board and personal computer have opened up vast possibilities in capturing, transferring, and analyzing detailed bases of information on the dynamics of fluid flow. It is up to us to see how we can use these capabilities to revolutionize the teaching, learning, and application of fluid dynamics. The curriculum plan presented in this paper is one author's view of how to start within the constraints of the present curriculum, and still be able to make a large improvement.

A closing note

Towards the end of June 1992, the National Science Foundation has informed the author that the plans outlined in this paper have been funded for implementation starting this year. This places great urgency on these plans, and provides a unique opportunity for experimentation. Suggestions and comments are invited from the interested reader: a prime objective of the NSF project is to ensure the widest communication, discussion, application, and associated improvement of these ideas.

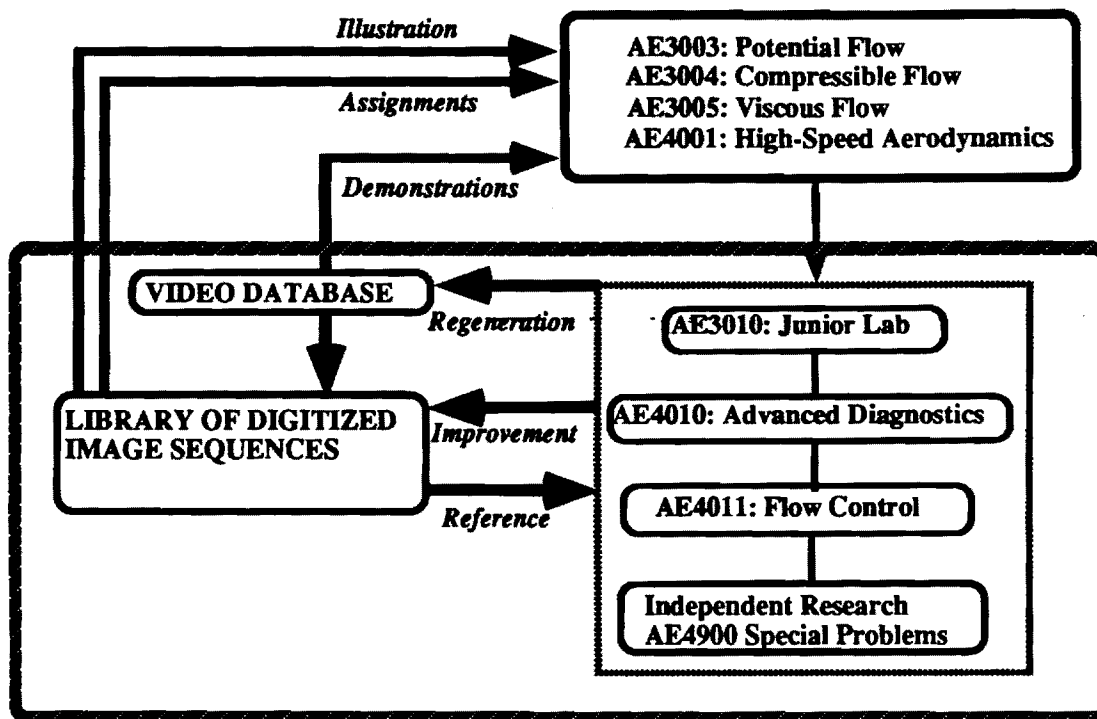
ACKNOWLEDGEMENTS

The author gratefully acknowledges the assistance of the many students who showed him what could be done. Particular thanks are due to Lenny Truett and Mark Burns, Teaching Assistants in AE3010, Robert Funk, and Paul Hubner for their help with the images of the tunnel start-up.

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17. Fawcett, P.A., Funk, R.B., Komerath, N.M., "Quantification of Canard-Wing Interactions by Spatial Correlation Velocimetry". AIAA Paper 92-2729, June '92.
18. Goodson, T., "An Investigation into the Measurement of Atmospheric Turbulence Through Cloud Motion". AE4900 Special Problem Report, School of Aerospace Engineering, Georgia Tech, June 1992.



FLOW IMAGING AND CONTROL LABORATORY

Figure 1: Integration of the planned Flow Imaging and Control Laboratory into the present aerospace engineering fluid mechanics curriculum.

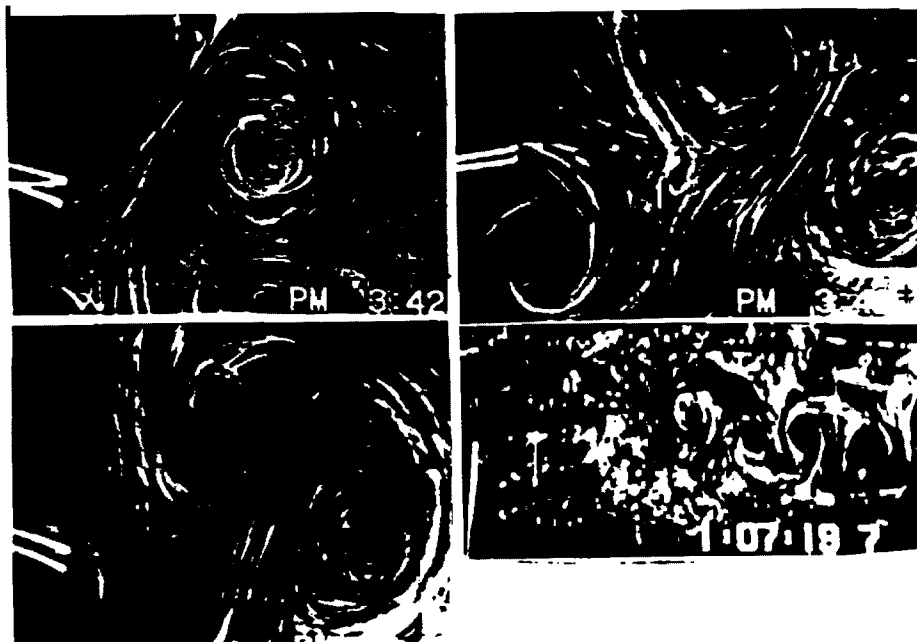


Figure 2: Digitized video sequence of vortex formation by an oscillating NACA 0012 wing, with a wide angle view of the wake. A copper vapor laser light sheet at the center of the 7' x 9' test section illuminates smoke at midspan of the 9"-chord, 42"-span wing. A Sony V-101 8mm camcorder was used at 1/500sec. exposure.



Figure 3: Asymmetric vortex flow due to forebody instability over a generic wing-body at high angle of attack.

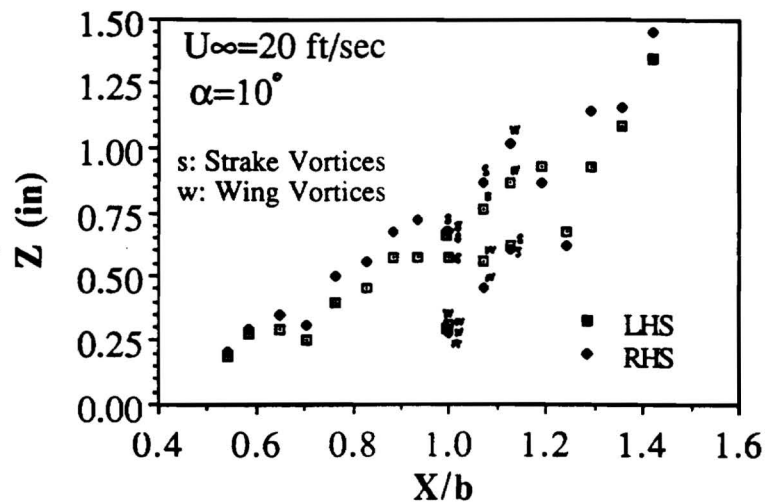


Figure 4: Plan view of trajectories of vortex centers, computed from digitized images after the asymmetry was removed by passive flow control. From Lenakos '92.

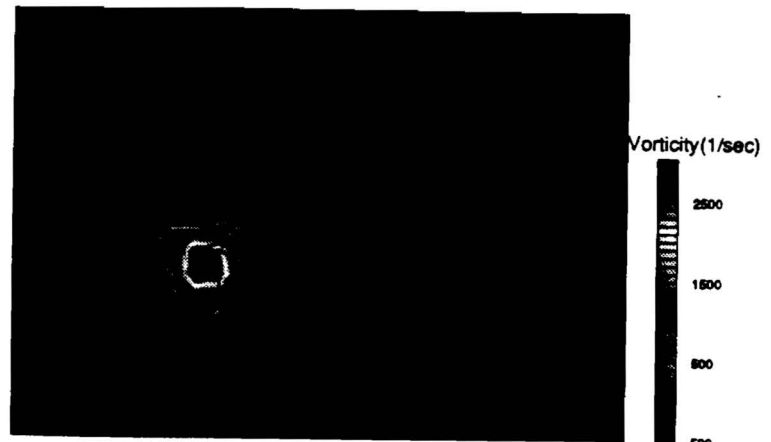
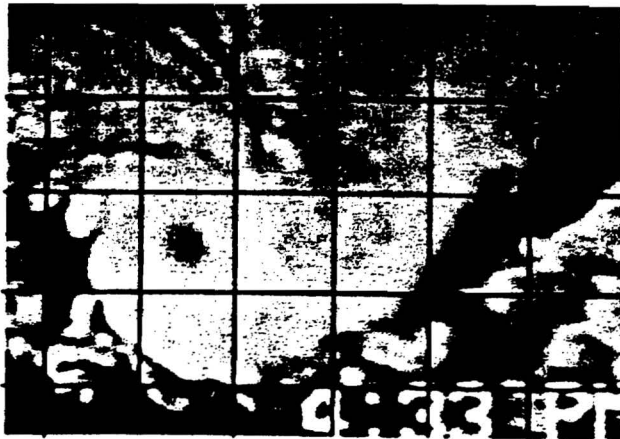
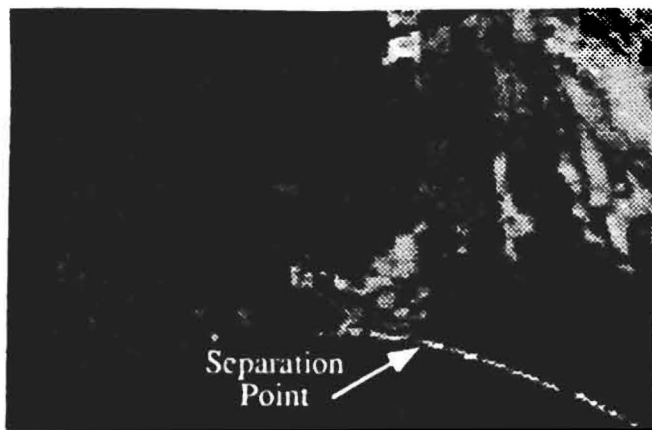
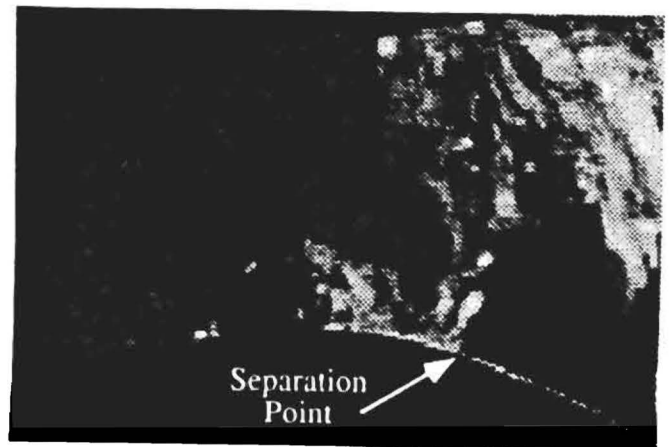


Figure 5: The roll-up of the inboard vortex sheet from a rotor in forward flight. (a) Image showing tip vortex and counter-rotating vortex structure. (b) Vorticity contours computed from velocity field measured by phase-resolved laser velocimetry. From Kim, '92.



a) Forward Separation Point



b) Intermediate Separation Point

Figure 6: Massive flow separation on a low-aspect ratio wing at moderate angle of attack, caused by interaction with the tip vortices from a rotor in low-speed forward flight. From Foley et al, '92.

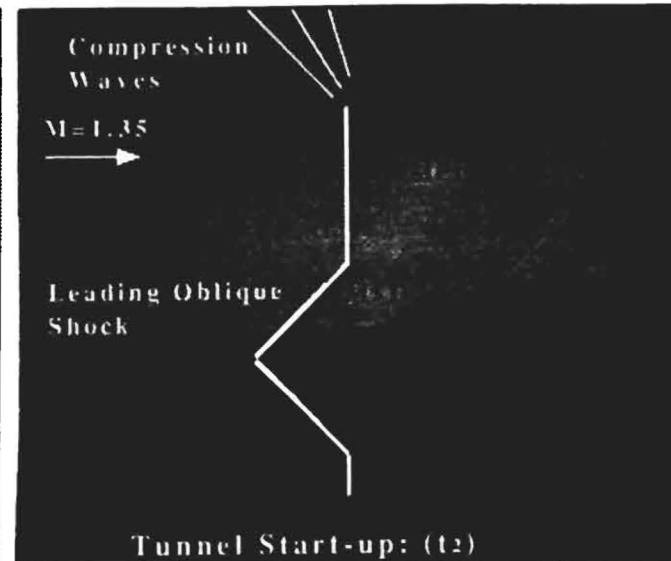
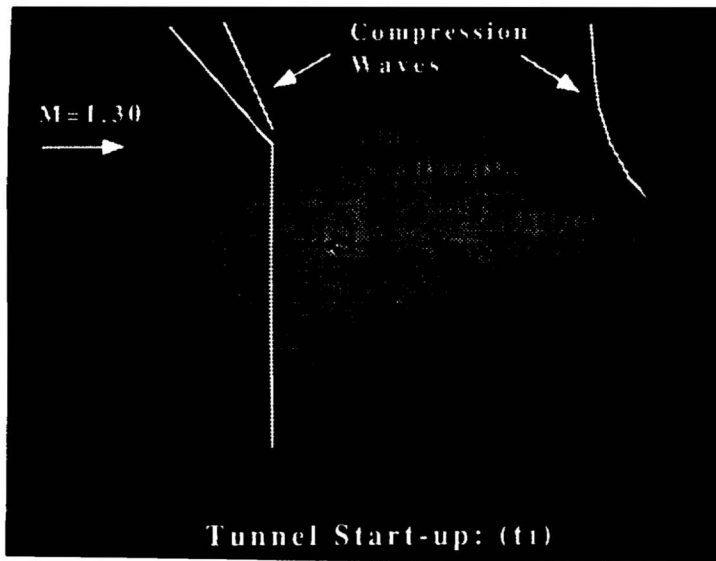


Figure 7: Two digitized color schlieren video frames captured during the start-up sequence of a blow-down supersonic tunnel, showing features observed around a wedge.



Figure 8: Spatial Correlation Velocimetry around an airfoil in a water tunnel. (a) flow image, (b) velocity vectors. From Komerath et al, '90.

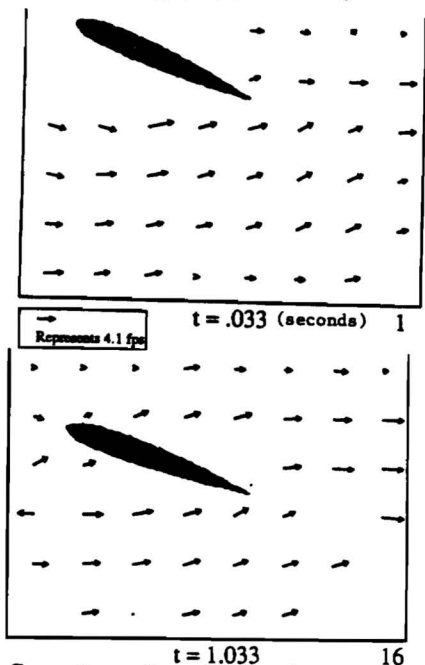


Figure 9: Samples of quantitative velocity field measurements during the plunging motion of an NACA0012 wing in the 7' x 9' tunnel, measured using SCV. From Fawcett et al, '91.

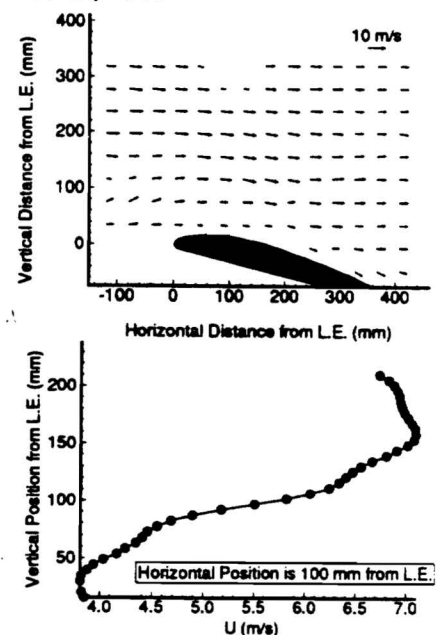


Figure 10: (a) Instantaneous velocity field measured over a wing with a stalled canard close upstream. (b) instantaneous velocity profile above the wing, showing jet-line flow due to canard interaction. From Fawcett et al, '92.

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Narayanan M. Komerath
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~~Georgia Institute of Technology~~
Georgia Institute of Technology
Atlanta GA 30332

NATIONAL SCIENCE FOUNDATION FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org.	Daniel E. Hodge - DLE	
2. Program Name	LABORATORY SECTION	
3. Award Dates (MM/YY)	From: 08/92	To: 07/95
4. Institution and Address	Georgia Institute of Technology Administration Building Atlanta GA 30332	
5. Award Number	9252303	
6. Project Title	Flick Imaging and Control Laboratory	

D

This Packet Contains
NSF Form 98A
And 1 Return Envelope

Grant Conditions (Article 17, GC-1, and Article 9, FDP-11) require submission of a Final Project Report (NSF Form 98A) to the NSF program officer no later than 90 days after the expiration of the award. Final Project Reports for expired awards must be received before new awards can be made (see NSF Grants Policy Manual Section 677).

or on a separate page attached to this form, provide a summary of the completed projects and technical information. Be sure to include your name and award number on each separate page. See below for more instructions.

PART II - SUMMARY OF COMPLETED PROJECT (for public use)

Summary (about 200 words) must be self-contained and intelligible to a scientifically literate reader. Without restating the title, it should begin with a topic sentence stating the project's major thesis. The summary should include, if pertinent to the project being described, the following items:

primary objectives and scope of the project
techniques or approaches used only to the degree necessary for comprehension
findings and implications stated as concisely and informatively as possible


Please See Attached Sheet

PART III - TECHNICAL INFORMATION (for program management use)

References to publications resulting from this award and briefly describe primary data, samples, physical collections, equipment, software, etc. created or gathered in the course of the research and, if appropriate, how they are being made available to the research community. Provide the NSF Invention Disclosure number for any invention.

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To the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinion) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or of individuals working under their supervision. I understand that willfully making a false statement or concealing a material fact in this report or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001).

	Nov 2, '95
Principal Investigator/Project Director Signature	Date

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MAILING INSTRUCTIONS
Return this *entire* packet plus all attachments in the envelope attached to the back of this form. Please copy the information from Part I, Block I to the *Attention block* on the envelope.

PART II: SUMMARY OF COMPLETED PROJECT

We have developed a new way of teaching fluid dynamics, enabled by interactive access to images of flows. Advanced instrumentation acquired using an NSF ILI grant enabled undergraduates to participate in developing an image database, several flow-control and diagnostic experiments, and advanced courses in Flow Diagnostics and Flow Control. Each course has a senior-elective and a first-year graduate version, enabled because most of the undergraduate team members joined graduate school. The courses were developed in an iterative manner, with the students involved as full partners in all aspects. In turn, this iterative technique was applied to the core courses and to advanced graduate courses, with documented success in improving comprehension, performance and interest. Besides the 4 new courses, the project also enabled revamping of a core aerodynamics course, and improvements in two other core courses. An interactive multimedia version of the aerodynamics course is being released on a CD-ROM; it is also being used by first-year graduate students and those studying for PhD Qualifying Exams to review the basics. Project results have been published in three refereed ASEE papers, two AIAA conference papers, NSF's Project Showcase, and are included in a new textbook. Our original hypothesis was that the efficiency and productivity of learning fluid dynamics can be increased substantially by providing visual access to the dynamics of fluids, by enhancing hands-on participation, and by integrating the challenge of flow control into the curriculum. The results have gone far beyond those proposed and anticipated, and the self-sustaining feature of the project has become evident. Others are adopting our techniques.

PART III: TECHNICAL INFORMATION

Publications

1. Komerath, N.M., "Flow Imaging and Control Laboratory: An Experiment in Iterative Learning". Annual Conference Proceedings of the ASEE, 1994, Vol. 1, p. 737-743.
2. Komerath, N.M., "Progress Towards Iterative Learning". Annual Conference Proceedings of the ASEE, Session 3536, paper No. 2, June 1995.
3. Komerath, N.M., "Experimental Curriculum in Diagnostics and Control of Unsteady Flows". To appear in the ASEE Journal.
4. Komerath, N.M., "Image Processing in the Fluid Dynamics Laboratory". AIAA Paper 92-4020, 17th Ground Testing Conference, Nashville, TN, July 1992.
5. Komerath, N.M., "Experimental Curriculum in Diagnostics and Control of Unsteady Flows". AIAA Paper 94-0850, Aerospace Sciences Meeting, Reno, Nevada, Jan. 94.

Course Descriptions

Undergraduate Flow Control: AE4813 Flow Control Techniques. 2-3-3.

Prerequisites: AE3010 or consent of instructor. Objectives of Flow Control. Techniques for reducing flow separation. Coanda effect, Vortex lift, Active energization. Techniques for reducing drag, Laminar flow control, shear layer re-direction, shock/particle interaction. Techniques for enhancing mixing: acoustic excitation, vortex pairing, passive edge shaping. Techniques for reducing vibrations and noise, cavity flow, vortex deflection. Laboratory experiments will include flow imaging demonstrations and two selected projects. Recent research results will be surveyed.

Graduate Flow Control: AE8123, 2-3-3, the graduate version of the course teaches more advanced topics on shear layer stability and expects research-quality experimental projects and literature reviews. It is more popular, because the prerequisites are the same as for AE4813; undergraduates are welcome and do well in this course, and graduate students from other schools find it easier to schedule this than a 4xxx-level course.

Senior Diagnostics: AE 4010 - Advanced Diagnostics in Fluid Dynamics 2-3-3.

Prerequisites: AE3005, AE3010 or consent of instructor: Overview of concepts and techniques used in experimental fluid dynamics. Introduction to experimental techniques;

flow visualization; statistical methods for turbulent flows; pressure, velocity, temperature, density, and reaction rate measurements. Laboratory operation, data acquisition, analysis, interpretation, and reporting.

Graduate Diagnostics: AE8113, the graduate version of the course goes deeper into advanced imaging technology and laser diagnostic theory. The experiments are expected to be performed to research standards, and involve substantial system development. Paper reviews are also expected to be at a higher level. Again, the graduate version is more popular than the undergraduate because of wider accessibility.

Facilities

Associated with this LLD grant, we also had an ILI equipment grant. Together with Georgia Tech Foundation funds and support from the research programs, these have enabled a unique capability to perform a variety of flow diagnostics and flow control experiments (see Refs. 3 and 5), and the removal of barriers between research and undergraduate instruction. Our undergraduates now perform superbly as research team members and the courses are linked tightly to research advances through these experiments and the multimedia-based dissemination route.

AeroCD

We have prepared the first version of AeroCD, an interactive compact disc dealing primarily with low-speed unsteady aerodynamics. It contains:

- (1) a dynamically-illustrated version of the course notes for our core aerodynamics course (in Microsoft Word™),
- (2) "FINWING", a standalone computer application to design and analyze wings,
- (3) "GTFOIL", another application to design airfoils, provided by Drs. Sankar and Latham under NSF SUCCEED program support,
- (4) several flow cases containing digitized full-screen image sequences of unsteady flows for generating homework assignments and physical insight
- (5) a "wind-tunnel fly-through" based on our 7' x 9' wind tunnel
- (6) a multi-level "Projector" version of the notes for the aerodynamics course, suitable for use by students at all levels ranging from high-school to graduate school, and
- (7) an interactive, multi-level course on High Angle of Attack Aerodynamics, generated by J.Paul Hubner while he was doing his PhD in this area. This goes from basics to current research results.

Student Participants (supported by this and related funding)

Name	Class when participant (1= Freshman, 4 = Senior)	Activity / Contribution
Earl Williams	2	Image-based curriculum; Water Table development
Chris Antalek	2	Equipment Inventory database; model-building
David Dishman	3 - 4	Diagnostics & Control Lab Experiment Design; Research Special Problems
James Aguirre	1	Water Tunnel Development & Testing; Water Tank Velocity Field Measurement
Michael Griffin	4	Flow Diagnostics Experiment development

Constantinos Malamas	2	Database development; computer systems; model-building
Bryan Palminier	2 - 4	Video Database, Catalog, Wind-Tunnel Fly-Through Development; Water Table Imaging; Image-based Assignment Development
Judy Garner	2	Literature Database
Tom Greulich	2 - 3	Wind tunnel operations / model design
Constantina Psomas	2 - 3	Water Tunnel Design
Peter Bellini	2 - 4	Image-Based Assignment development; Water Table Imaging experiments
Richard Ames	3 - 4	Styrofoam Wing Construction; aircraft model building; Image Processing and Control Software; Robotic Manipulator Computer-Aided Design
Jason Mucha	3	Water Tunnel Development
Howard Hamilton	3 - 4	Holography Exploration; Laser Velocimetry
Jay Bailey (Summer Intern from Wofford College, Spartanburg)	3 - 4	Study of Measurement Accuracy; Development of Operations & Safety Procedures
James Gregory (assisting Clark Atlanta U. researchers)	3	Spatial Correlation Velocimetry for Measurement of Simulated Heart-Valve Flows
Alan Schiaffino	4	Multimedia-based Aerodynamics course (AeroCD) development
Lilliana Villareal	3 - 4	Multimedia-based Aerodynamics course (AeroCD) development; aerodynamics research

Iterative Curriculum

The most significant result of this project is the confirmation of our hypothesis that an Iterative (rather than purely Sequential) Curriculum can be made to work, and produces excellent results, in engineering school. Technology is used to enable students to become proficient by iteration without any grade penalties, so that perspective and insight are gained along with detailed technical competence in the discipline. The best proof of its success is that (a) formerly-skeptical colleagues are talking seriously about generating "CDs" for their courses, (b) the students are using these things without being asked to do so, and (c) undergraduates who went through such courses merge into research and design project teams with much less uncertainty and confusion, and produce excellent work.

PART IV -- FINAL PROJECT REPORT -- SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in response to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the information.

Please enter the numbers of individuals supported under this grant.

Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants ¹	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens							14	3		
B. Total, Permanent Residents	1									
U.S. Citizens or Permanent Residents ² :										
American Indian or Alaskan Native										
Asian	1									
Black, Not of Hispanic Origin							3			
Hispanic								2		
Pacific Islander										
White, Not of Hispanic Origin							11	1		
C. Total, Other Non-U.S. Citizens							1			
Specify Country							1			
1. Greece										
2.										
3.										
D. Total, All participants (A + B + C)	1						15	3		
Disabled³										

☐ Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

All information above is guesswork except the P.I.'s data.

¹ Category includes, for example, college and precollege teachers, conference and workshop participants.

² Use the category that best describes the ethnic/racial status for all U.S. Citizens and Non-citizens with Permanent Residency. (If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)

³ A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. (Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

PACIFIC ISLANDER: A person having origins in any of the original peoples of Hawaii; the U.S. Pacific territories of Guam, American Samoa, and the Northern Marianas; the U.S. Trust Territory of Palau; the islands of Micronesia and Melanesia; or the Philippines.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.